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## Three Essays in Environmental and Natural Resource Economics

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# Three Essays in Environmental and Natural Resource Economics

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This Dissertation is dedicated to Amy Benold Heutel

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## Three Essays in Environmental and Natural Resource Economics

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Environmental regulations that grandfather existing plants by not holding them to the same standards as new plants may have the unintended consequence of retarding new investment. In my first essay, I develop a dynamic model of a plant's optimal scrapping decision, which depends on environmental policy. Using data from electric power plants, I estimate the parameters of the model and assess the impact of the Clean Air Act on emissions and plant productivity. Over the 1990s, grandfathering provisions increased emissions by about 78% and decreased productivity by about 3%. Furthermore, I show that under certain reasonable parameters, given grandfathering, total discounted environmental damages can be reduced by weakening environmental regulations.

Regulations that restrict pollution by firms also affect decisions about use of labor and capital. They thus affect relative factor prices and output prices. My second essay studies the general equilibrium impacts of environmental mandates on the wage, the return to capital, and relative output prices. It looks at four types of mandates and for each determines conditions that place more of the burden on labor or on capital. Stricter regulation does not always place less burden on the factor that is a better substitute for

pollution. Also, a relative restriction on the amount of pollution per unit output creates an "output-subsidy effect" that affects factor prices in a different way than the traditional output and substitution effects.

Public goods are provided by both governments and individuals. In response to an increase in government spending on a public good, individuals may reduce their contributions. This "crowding-out" effect can occur in the opposite direction. If a government sees that private donations to a charity have risen, then it may reduce its public funds to that charity. While the literature focuses on how government spending crowds out individual giving, the purpose of my third essay is to examine crowding out in the opposite direction? I test for crowding out using data on private and public contributions to environmental charities. I find evidence that government grants crowd out private donations, but evidence is mixed on crowding out in the opposite direction.

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## Chapter 1: Plant Vintages, Grandfathering, and Environmental Policy

Regulations often contain grandfathering provisions, where facilities already built or workers already employed at the time of passage are not subject to the new standard. While the reasoning for such provisions may relate to fairness, such as a wish not to "change the rules in the middle of the game," they often come with unintended consequences. By giving different incentives to grandfathered agents and non-grandfathered agents, the regulations can lead to perverse outcomes. The federal policy of New Source Review (NSR) for major sources of air pollution may be one such regulation. By mandating that any new pollution sources (such as a power plant) or any existing sources that propose major modifications meet very strict standards for pollution control, the rule may keep older facilities from making modifications or from closing outright and being replaced by newer ones. If older facilities are dirtier than newer ones, due to physical depreciation or technological growth, then this increases pollution. For the same reasons, older facilities may be less efficient, and so the disincentive for new investment may also reduce productivity.

An early examination of this effect is studied in Gruenspecht (1982), who looks not at stationary air pollution sources but at automobiles. He finds that stricter vehicle emissions standards, which apply only to new cars and hence effectively grandfather old cars, lead to a short term increase in emissions. Nelson et. al. (1993) find that environmental regulations increase the age of capital but not the level of emissions, while Levinson (1999) finds no significant difference in capital vintage between states with and without grandfather provisions. Maloney and Brady (1988) and List et. al. (2004) also find perverse effects of grandfathering in the electric power industry and in manufacturing plants in New York state, respectively. Finally, Bushnell and Wolfram (2006) find that grandfathering in the Clean Air Act (CAA) increases the lifetimes and decreases the capital expenditures of coal-fired power plants but has no effect on their operating costs or fuel efficiency.

The purpose of this paper is to determine how grandfathering provisions in environmental policy affect both the pollution from and the productivity of electric power plants. I develop a dynamic, discrete choice model of each facility's decision about whether to invest in new capital. This decision is affected by the relative profitability of new capital, the costs of upgrading, and environmental regulations. Newer capital pollutes less, and hence stricter environmental policy without grandfathering provides an extra incentive to upgrade. Yet stricter environmental policy with grandfathering may provide a disincentive to upgrade. Using 1998-2000 emissions and 1990-2000 vintage data from U.S. electric power plants, I estimate the parameters of the model. Finally, I use the estimated model to simulate the effects of certain policies and determine how grandfathering in the CAA has impacted emissions, plant births, and productivity.

The model presented here is closely related to the capital investment models in Cooper and Haltiwanger (1993) and Cooper et. al (1999). As in those papers, firms face a discrete choice of whether or not to upgrade their capital. They show that the cross-sectional distribution of capital vintage affects aggregate investment. For example, if in one period a large fraction of plants are old and hence choose to adjust, then the following period a large fraction will be new, and the investment rate will drop sharply. Here, newer capital is modeled to be more productive and less polluting, so similar effects yield a fluctuating level of aggregate investment and emissions.[1]

I find a significant effect of grandfathering in environmental regulations on both emissions and productivity. Using the model to simulate the CAA and counterfactuals, I find that if grandfathering provisions were eliminated in 1990, emissions from power plants would be 50% lower and productivity of power plants would be 3% greater by 2000. However, if the CAA were weakened or entirely rescinded in 1990, emissions would decrease and productivity would increase by 2000. This occurs for the same reason that strengthening a grandfathered standard can have a short term perverse effect. When the grandfathered CAA is eliminated, plants that are currently grandfathered lose

[1] Using a similar model, Adda and Cooper (2000) study individuals' decisions on new car purchases. They find similar effects arising from the cross-sectional distribution of auto vintages. Their model is tested using data from France, and they simulate the effects of a particular policy that subsidized new car purchases to promote production.

their valuable grandfathered status, and hence they lose their disincentive to invest. Furthermore, with a sufficiently high discount factor, this short-term decrease followed by a long-term increase in emissions raises social welfare. Therefore, weakening or rescinding the CAA may reduce the total discounted damages from pollution.

Grandfathering, or vintage-differentiated regulation, appears frequently outside of the CAA, both in environmental and non-environmental laws. Corporate average fuel economy (CAFE) standards and manufacturers emissions rate standards apply only to new cars, so old cars are grandfathered. The Clean Water Act and the Safe Drinking Water Act both set differential standards for water treatment plants based on when they went into operation. Fire sprinklers are required in new buildings, but existing buildings are often not required to have them unless they are renovated. Zoning ordinances generally do not apply to businesses or homes built before the ordinance went into effect. While tolls are forbidden in the federal highway program, the program does include some roads that were built as toll roads before joining the program. Given the prevalence of grandfathering, it is important to study these effects, including any potentially perverse or counterproductive effects.

The next section below presents the model. In section 1.2 I describe the data, and I present the estimation strategy in section 1.3. Section 1.4 presents the simulations, and section 1.5 concludes.

**1.1 Model**

I consider the behavior of a profit-maximizing one-plant firm. This model could be generalized to multi-plant firms, but the assumption that each individual plant's maximization decision is independent leads to identical results. Each plant faces a single discrete decision: whether or not to update its production technology.[2] Newer plants are

[2] For simplicity and tractability, this choice is assumed to be binary, rather than choosing from a continuous level of capital investment. Doms and Dunne (1998) and Nilsen and Schiantarelli (2003) find that investment is mostly "lumpy." I do not capture the gradual capital stock improvements a plant undergoes; I focus only on plant replacement. The model also does not consider entry and exit. Any plant that exits is immediately replaced by a new plant that enters, so that the total size of the industry is fixed. In the data, the vast majority of the electric utilities are present in every year, indicating that the utility-level industry makeup is about constant, and entry and exit are not prevalent in this industry.

both more productive and less polluting. Consider a plant of age $v$. If it updates, its age becomes $v = 1$. If it does not update its age stays at $v$, and its next-period age is $v + 1$.

Let $Af(v)$ represent the productivity of a plant of age $v$, where $A$ is a multiplicative productivity shock. Emissions, like productivity, are a function of plant vintage: $e_t^i = B_t^i g(v_t^i)$, where $B_t^i$ is a shock to emissions intensity for plant $i$ at time $t$. Environmental policy is modeled by a tax[3] $_t$ on emissions $e_t^i$. Older plants are assumed to be less productive $(f'(v) < 0)$ and dirtier $(g'(v) > 0)$.[4] Define the choice variable $z_t^i$ to equal one when plant $i$ updates in period $t$, and zero if it does not. The profit function of plant $i$ in period $t$ is

$$y_i^i = A_t^i f(v_t^i)(1 - \lambda z_t^i) - z_t^i F - u_t^i \tau_t e_t^i,$$

where $v_t^i = 1$ if $z_t^i = 1$. The parameters $\lambda \in [0,1]$ and $F$ represent adjustment costs. If a plant adjusts in period $t$ it faces not only a fixed cost, $F$, but also a proportional cost, through losing a fraction of its output that period. The term reflects the fact that, during periods where capital is updated, a fraction of time must be spent on that adjustment, which reduces output and therefore profits. Therefore, in more productive periods, adjustment is costlier. Finally, each plant has an additional state variable $u_t^i$ that indicates its grandfathered status. It equals zero if a plant is grandfathered and not subject to the environmental policy, and it equals one if the plant is subject to the policy. Once a plant adjusts, it loses its grandfathered status and cannot regain it; the evolution of $u_t^i$ is irreversible. In addition to the endogenous choice of adjustment $z_t^i$, plants are also subject to being forced to adjust in the next period with exogenous probability . This could represent the probability of a plant breaking down or being forced to shut down for

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[3] The model was also developed with an emissions standard, rather than a tax, where plants are not allowed to emit above a particular threshold, with similar results.

[4] While this model does not explicitly incorporate technological growth, it is implicit in the decreasing productivity function for older capital. Older capital is less productive both absolutely, because of real depreciation, and relatively, because of the improved technology of newer capital. Thus "capital depreciation" as used below encompasses both physical depreciation and obsolescence. These two features could be separately included in the model, where the assumption of an exogenous growth rate would make the problem identical to the one presented here. See Cooper et. al. (1999).

reasons other than its age.[5] Plants maximize discounted expected lifetime profits $E_0 \sum_{t=0}^{\infty} \beta^t y_t^i$ , where $E_0$ is the expectation operator at $t = 0$ and  is the discount factor.

The plant's choice can be written as a dynamic programming problem:

$$V(v, u, A, B) = \max[V^N(v, u, A, B), V^A(v, u, A, B)]$$

$$V^N(v, u, A, B) = Af(v) - \ uBg(v) + \ (1 - \ ) E_{A'|A, B'|B} V(v+1, u, A', B')$$

$$+ \quad E_{A'|A, B'|B} [V(1, 1, A', B') - F - \ A'f(1)]$$

$$V^A(v, u, A, B) = Af(1)(1 - \ ) - F - \ Bg(1) + \ (1 - \ ) E_{A'|A, B'|B} V(2, 1, A', B')$$

$$+ \quad E_{A'|A, B'|B} [V(1, 1, A', B') - F - \ A'f(1)]$$

The first equation indicates that plants will optimize over adjusting ($V^A$) or not adjusting ($V^N$). The second equation indicates that, without adjusting, a plant's next-period vintage is increased by one year and it maintains the same grandfathering status. The third equation indicates that, with adjustment, output is reduced by a factor  and a fixed cost $F$, next period's vintage is one, and next period's grandfathering status is one, meaning that the plant is not grandfathered anymore. Whether plants adjust or not, with probability  the plant must be scrapped in the following period. In this case, the next period plant's age is one, it has lost its grandfathering status, and it is forced to pay the fixed and proportional adjustment costs.

The dynamic programming problem generates a hazard function for adjustment: $H(v, u, A, B)$. This represents the probability that a plant of vintage $v$ and grandfather status $u$, subject to shocks $A$ and $B$, will adjust its capital stock. For a plant with full information, this value is either zero or one. If either shock is unobservable to the plant or the econometrician, then $H(\cdot)$ is a probability that the unobservable shock takes a value such that adjustment occurs. In the following section, I impose assumptions on the distribution of the two shocks to estimate the model. Even without such assumptions, though, certain properties of the hazard function can be proven. Proofs are in Appendix A1.

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[5] This is similar to the probability of automobile breakdown in Adda and Cooper (2000). It is added to the model to allow it to more closely match the data, where in fact plants of even young ages do occasionally shut down.

*Proposition 1:* $H(v, u, A, B)$ *is increasing in* $v$.

The older a plant, all else equal, the more likely it is to adjust its capital.[6] This is intuitive since older plants have both reduced productivity $(f'(v) < 0)$ and increased emissions tax expenditure $(g'(v) > 0)$. It can also be proven that a grandfathered plant is less likely to adjust than a non-grandfathered plant, all else equal.

*Proposition 2:* $H(v, u = 0, A, B) < H(v, u = 1, A, B)$

Once a grandfathered plant adjusts, it loses for all future periods its exemption from that environmental policy. This is an additional disincentive for a grandfathered plant to adjust, and hence its probability of adjustment is always lower.[7]

## 1.2. Data

I use this model to estimate the impact of grandfathering in the Clean Air Act (CAA) of 1970 on the electric power generating industry.[8] The CAA is an appropriate policy to consider because of its explicit grandfathering of existing sources. Section 111 of the law gave EPA the power to set binding emissions standards on all new sources of emissions - the New Source Performance Standards (NSPS). Regulation of existing plants was left up to the states, and is likely to be less strict.[9] The plants were grandfathered for reasons of efficiency (it is costlier to retrofit existing plants than new ones), equity (it is unfair to "change the rules of the game mid-stream" by regulating existing plants), and politics (potential facilities have less clout than existing ones).[10]

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[6] This first proposition is analogous to Proposition 2 in Cooper et. al. (1999), but they do not consider grandfathering.

[7] Note that the irreversibility of the plant's decision in this model arises from the policy, not from the technology as in Dixit and Pindyck (1994, pp. 405-412). They present a real options model of the behavior of electric utilities. In their model, plants can buy or sell emissions permits, switch to low-sulfur coal, or install scrubbers. The latter two decisions are irreversible, but their irreversibility arises from the technology available to the plants, not from policy. Their model is more complex in that they explicitly model specific investments that utilities can undertake, and they consider regulatory uncertainty, but they do not model grandfathering.

[8] Technically, the CAA was passed in 1963 and amended in 1970, but the 1970 amendments are often referred to as the "Clean Air Act of 1970" because they contained the bulk of the regulations.

[9] The regulations differ by state, and such heterogeneity is not captured in this model. Rather, I simplify the policy by assuming that all grandfathered plants are free from regulation, and all non-grandfathered plants are subject to the same regulation.

[10] Stavins (2005) discusses the effects of grandfathering of environmental policy in many contexts. While Greenstone (2002) studies the impact of the CAA on employment, capital stock, and output, and Keohane

These standards are not a simple emissions tax as modeled above. Rather, the law allows states to craft plans to attain air quality improvements. However, the multitude of standards facing plants creates a shadow price for pollution, or a virtual tax on pollution that corresponds to the tax in the model.[11]

A problem with applying this model to data on electric utilities is how they depart from the behavior of competitive, profit-maximizing firms. During the end of the sample period of 1990-2000, electricity markets were being deregulated, and ample evidence exists of market power in this sector. For example, Borenstein et. al. (2001) find evidence of monopsony power from a particular buyer in California's deregulated electricity market in 2000, and Joskow and Kahn (2002) find evidence that energy *suppliers* exercised market power in the same situation. The model here does not explicitly consider market power but does implicitly allow for it. Price does not enter the model; rather, plants maximize an expression that is a function of their vintage and random shocks. If plants exercise market power, then whatever rents they collect are in the maximand in this model. Also, given that utilities are not profit-maximizers, the maximand need not be considered "profit," but the plant's decision can be characterized as minimizing costs given consumers' electricity needs.[12] Rothwell and Rust (1997) model nuclear power plants as profit-maximizers, though most are owned by public utilities, citing empirical evidence suggesting that they in fact behave as profit-maximizers, and Che and Rothwell (1995) suggest that the presence of incentive-based

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et. al. (2006) study how electric utilities respond to both the threat of enforcement of NSR violations and the enforcements themselves, neither paper estimates the effects of grandfathering.

[11] The model could apply to a cap and trade program for emissions permits, such as the one for $SO_2$ emissions under the 1990 CAA Amendments. Phase I of that market began in 1995 but applied to only 110 power plants. Phase II, which covered many more plants, did not begin until 2000. With tradable permits, the firm's value function is identical to the one here; the only difference is that under a cap and trade program, the virtual emissions tax is actually the permit price, and it is endogenously determined.

[12] Cooper and Ejarque (2003) incorporate market power simply by modeling profits as a concave function of the capital stock. The model here allows for this possibility since the capital stock is not explicitly modeled; a plant's productivity is measured solely by its age. Another issue is the interaction between environmental regulations and other regulations utilities face. Coggins and Smith (1993) and Fullerton et. al. (1997) examine how tradable emissions permits function in an industry that faces rate-of-return monopoly regulation. They find that the cost savings from allowing permit trading depends upon the nature of the monopoly regulation. Burtraw and Palmer (2006) find that the distribution of the costs of instituting a carbon emissions permit market for power plants depends greatly on whether the plants are regulated or act competitively. All of these possibilities are allowed here.

regulations has moved utilities towards acting more like profit-maximizers.[13] Price regulation of power plants may impact the model only if the regulation changes during the sample period. It was only during the last years of the 1990s that some states were beginning to deregulate prices or differently regulate power plants. To the extent that this change in the regulatory regime affects a plant's decision making, this may impact the results of the estimation process.[14]

Emissions data come from the EPA's Emissions and Generation Resource Integrated Database (eGRID).[15] This panel data set provides emissions and generation information on electric power plants from 1996 through 2000. Plant-level data are available for both nonutility-owned and utility-owned plants from 1998–2000, but plant-level data from most nonutilities are unavailable from 1996-1997. Furthermore, the data for the first two years are less reliable than those from the latter three years. Therefore, I use the last three years of data only. Because the data used on plant vintages, described below, contains only utilities, I restrict this data set to utilities only. The data set contains each plant's annual emissions of $NO_X$, $SO_2$, and other pollutants, as well as the type of plant, primary fuel input, total heat input (in MMBtu) and total output (in MWh). Data on age are available not at the plant level but at the generator level. Each power plant may have more than one generator, and each generator may have come online in a different year. Therefore, each moment is evaluated at the plant level, and I sum over all of the generators in that plant.

I use the eGRID emissions data to estimate the function $e_t^i = B_t^i g(v_t^i),$ which gives emissions $e_t^i$ as a function of age $v_t^i$ and a multiplicative random shock $B_t^i$. Rather than use the absolute level of emissions, I set $e_t^i$ equal to the emissions intensity of plant $i$ in year $t$, defined by tons of emissions of $SO_2$ per MMBtu of heat input.[16]

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[13] The specification modeled here is identical to one where plants are cost minimizers rather than profit maximizers, if the productivity function $f(v)$ is replaced with a cost function $h(v)$.

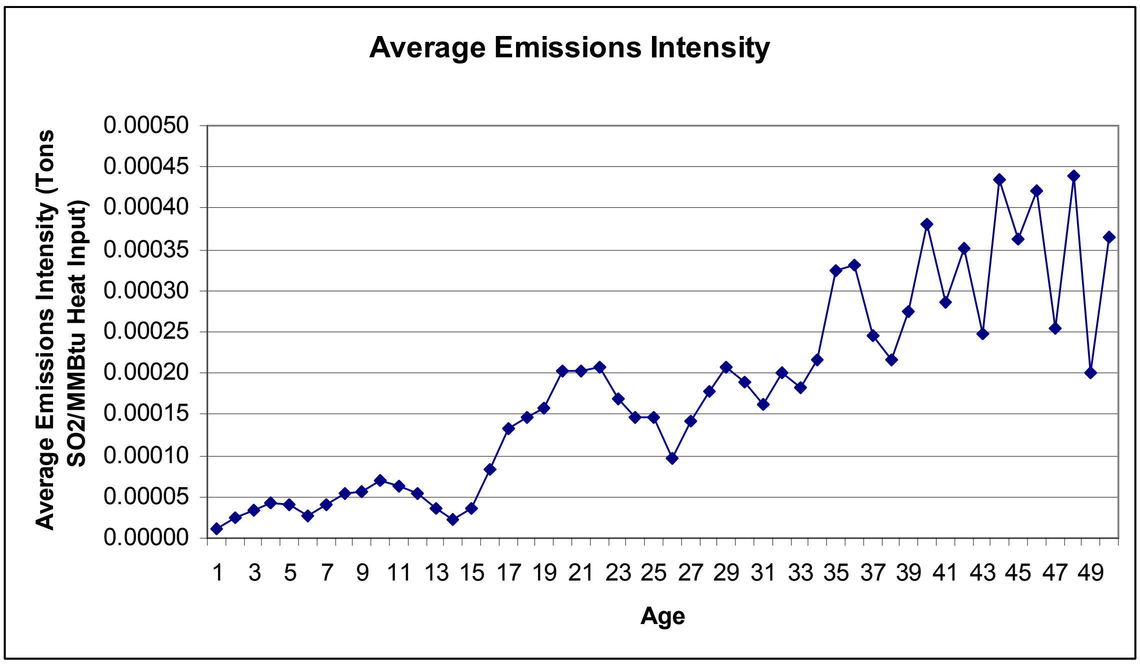
[14] If the sample is restricted to only the years before 1998, when deregulation began in several states, the moments used to estimate the parameters are similar to the moments from the whole sample.

[15] Available online at www.epa.gov/cleanenergy/egrid.

[16] I choose to focus on $SO_2$ because it is one of the criteria pollutants from the Clean Air Act. Using $NO_X$ instead yields similar results, though the increasing relationship between age and emissions intensity is less strong. Rather than defining emissions intensity as emissions per unit heat input, it can also be defined as emissions per unit output (power generated) with similar results.

Absolute emissions levels are not as closely related to age. Older plants are dirtier but are used less frequently; therefore the relation between age and absolute emissions is not monotone increasing. With emissions intensity, however, the results are conformable to assumptions of the model: older plants emit proportionately more, on average. In Figure 1.1, I plot the average emissions intensity by age from generators in the sample years. The clear upward trend indicates that newer plants are on average cleaner than older plants. The average six-year-old plant emitted 0.0000410 tons $SO_2$ per MMBtu heat input, whereas the average 30-year-old plant emitted 0.000190 tons $SO_2$ per MMBtu heat input.

**Figure 1.1**




*Notes:* Data source is EPA eGrid data., 1998-2000. The *x*- axis is the age of the generator; the *y*-axis is the average emissions intensity for generators of that age.

The emissions intensity function is estimated using the generalized method of moments (GMM). I allow for two different specifications of the function $g(v)$: linear and geometric. The multiplicative random term $B$ is assumed to be distributed log-normally with a median of one. In both estimations I use the first three moments of the emissions intensity equation to estimate the three parameters. The results are summarized in Table

1.1. In the geometric specification of $g(v)$, the parameter $\;_g$ represents a plant's emissions intensity depreciation: the value of 0.99 indicates that a plant gets about 1% dirtier for each year of age. This relationship could also arise from vintage effects rather than age effects. That is, a ten-year-old plant built in 1980 is no dirtier than a brand new plant built in 1980, but a ten-year-old plant built in 1980 is dirtier than a ten-year-old plant built in 1990. Because the data I have include plants from a wide range of vintages, but for only three years, it is difficult to differentiate age effects from vintage effects (for each vintage, I have only plants covering three years of age). However, this distinction becomes irrelevant when the model is assumed to incorporate both physical depreciation and technological change, so that $g(v)$ represents the level of emissions relative to the best available technology. Thus $g(v)$ is increasing both because a plant gets dirtier as it ages and because newer plants are cleaner due to technological improvement.[17]

**Table 1.1**

| **Emissions function estimation results** $e_i = B \cdot g(v)$, $B \sim \text{Lognormal}[0, \;_B^2]$ | | | |
|---|---|---|---|
| Linear: $g(v) = a_1 + a_2 v$ | $a_1$ | $a_2$ | $\;_B^2$ |
| | $-1.0549\times10^{-4}$ ($4.4751\times10^{-6}$) | $6.5783\times10^{-6}$ ($1.3469\times10^{-10}$) | .1789 (.0493) |
| Geometric: $g(v) = A_g(1 - \;_g^{v-1})$ | $A_g$ | $\;_g$ | $\;_B^2$ |
| | .0015 (.0026) | .9982 (.0032) | .5430 (.0560) |

*Notes*: Data source is EPA eGrid data, 1998-2000. The left-hand side of the equation, emissions intensity, is defined as tons $SO_2$/MMBtu heat input. Estimates are from GMM, using the first three moments of the emissions intensity equation $e_i = B \cdot g(v)$. Standard errors are in parentheses.

While I have reliable emissions data for only three years, more thorough data on plant characteristics are available from 1990-2000 from the Energy Information Administration (EIA). These data come from the Annual Electric Generator Report collected from all utilities for these years, and they contain the generator vintage for all generators of all plants in the sample.[18] Because multiple generators at a plant can be of

[17] This is the same point brought up in footnote 4 with regards to productivity depreciation.
[18] The data are available at http://www.eia.doe.gov/cneaf/electricity/page/eia860a.html.

different ages, the unit of observation in this data set is the generator, not the plant. For the purposes of this model and mapping to the CAA, each generator is considered either grandfathered or not grandfathered from that law. The CAA was passed in 1970, so all generators built that year or earlier are considered grandfathered in this estimation, and the rest are not. This mapping may not be perfect, since the review process for newly built plants, New Source Review (NSR), may be triggered by making significant changes to an existing plant even without building a brand new generator.[19] Furthermore, the building or modification of one generator may trigger NSR for all other unmodified generators at that plant, which would not be captured by this specification. However, this is unlikely since NSR typically applies to the generating unit, not the entire plant.

### 1.3. Estimation

Because of the discrete nature of the generators' decisions in the model, I have no analytical mapping of the model parameters to the data. That is, no moment conditions are available to use GMM. Therefore, I estimate the parameters of the model using the simulated method of moments (SMM).[20] From the data, I create a vector of moments . I choose a set of parameters and solve the model using value function iteration. With the model solved, I simulate "data" and create a simulated set of those moments $_s( )$. I repeat the simulation $S$ times. The final estimate of is the set of parameters that minimizes $[\omega - \frac{1}{S}\sum_s \omega_s(\Theta)]W[\omega - \frac{1}{S}\sum_s \omega_s(\Theta)]'$, where $W$ is a weighting matrix. The

[19] Routine maintenance and repair do not trigger NSR, but major modifications that increase a plant's emissions do. The line between these two types of investment has often been murky (see Stavins 2005, p. 10-11). In August 2003 the EPA issued the Equipment Replacement Provision (ERP), which states that any repair or maintenance expenditures less than 20% of the capital costs of the plant are considered routine and do not trigger NSR. However, as of September 2006, ten cases were pending in court regarding investments that utilities felt were routine modifications, but that the government felt should trigger NSR. See http://www.eenews.net/features/special_reports/nsr/enforcement_chart.php for a list of the cases. Since the model here concerns only a generator's binary decision to update or not, I do not consider small adjustments to the generator's capital. An alternative model could include a continuous choice for investment, with a cut-off level of investment over which NSR is triggered.

[20] For examples of this method, see Cooper et. al. (2004), Adda and Cooper (2003), Gourieroux and Monfort (2003), Lee and Ingram (1991), or McFadden (1989).

weighting matrix used is an estimate of the optimal weight matrix.[21] Given this weight matrix, the variance of the parameter estimate is given by $(1+\frac{1}{S})[\frac{\partial \omega'}{\partial \Theta} W^{-1} \frac{\partial \omega}{\partial \Theta'}]^{-1}$, which can be approximated numerically.

Table 1.2 presents summary statistics from the data, including the moments that will be used in the estimation procedure. These moments are the percentage of generators adjusting in certain age and grandfathering categories. Panel A of Table 1.2 lists six different age categories, and the adjustment percentages for grandfathered and non-grandfathered generators in each age bracket. Some of the entries are missing because of the years available in the data set. The data are from 1990-2000, so all generators younger than 20 years old are younger than the CAA and hence not grandfathered. Likewise, all generators older than 30 years old are grandfathered. Only those generators between 20 and 30 years old can be either grandfathered or not grandfathered in the years captured in the data.

[21] This estimate of the optimal weight matrix is the estimated covariance matrix of the difference between the actual and simulated moments. See Adda and Cooper (2003), p.89, or Gourieroux and Monfort (1996), p. 32 for the formula.

**Table 1.2**

| **Data Moments** | | |
|---|---|---|
| Panel A: Adjustment Moments | | |
| Generator Age | Percentage of Generators Adjusting, Grandfathered | Percentage of Generators Adjusting, Not Grandfathered |
| 10 years or less | NA | 1.25 |
| 11 to 20 years | NA | 1.44 |
| 21 to 25 years | 0.90 | 1.28 |
| 26 to 30 years | 2.46 | 5.25 |
| 31 to 40 years | 2.72 | NA |
| Greater than 40 years | 3.37 | NA |
| Panel B: Annual Moments | | |
| Year | Age | Fraction Grandfathered |
| 1991 | 33.628 (20.930) | 0.738 |
| 1992 | 33.429 (21.512) | 0.707 |
| 1993 | 34.425 (21.512) | 0.707 |
| 1994 | 34.862 (21.661) | 0.697 |
| 1995 | 35.636 (21.745) | 0.695 |
| 1996 | 36.260 (21.896) | 0.688 |
| 1997 | 36.623 (22.132) | 0.674 |
| 1998 | 36.988 (22.157) | 0.666 |
| 1999 | 36.725 (22.384) | 0.641 |
| 2000 | 36.313 (22.864) | 0.616 |

*Notes*: From EIA Annual Electric Generator Report, 1991-2000. Standard deviations are in parentheses. Generators are defined as being grandfathered if their in-service date is 1970 or earlier. Entries listed NA are not available; neither grandfathered generators younger than 20 nor non-grandfathered generators older than 30 are in the data.

The entries in Panel A of Table 1.2 are the annual fraction of generators, in each category, in percent, that retire from the active fleet of operating generators per year. All of these fractions are low, always less than six percent. Furthermore, these moments conform to Propositions 1 and 2. Proposition 1 says that older generators are more likely to adjust, which holds for both grandfathered and non-grandfathered generators in these data (with one exception: non-grandfathered generators aged 21-25 actually have a slightly lower adjustment rate then those aged 11-20). Proposition 2 says that grandfathered generators are less likely to adjust than non-grandfathered generators, for a particular vintage. This also holds true in the data of Table 1.2, where a higher fraction of generators aged 21-25 and 26-30 adjust if not grandfathered than if grandfathered.

Panel B of Table 1.2 lists other summary statistics: the average age of the generators each year (with the standard deviation in parentheses) and the fraction of generators grandfathered in that year. The percentage of generators built before 1970 decreases over time from 74% to 62%, reflecting the irreversible nature of the grandfathering. While I estimate the model using the moments from Panel A of Table 1.2, the second set of moments is here to see how well the model does in predicting moments other than those used to estimate it.

The structural estimation model here differs from the estimation techniques used in previous literature related to the CAA. The technique here is the first that is both structural and dynamic. Furthermore, rather than identifying the effect of grandfathering directly using the plant's age, other papers have indirectly identified it only from information on whether the plant was located in an attainment or a non-attainment county.[22] Bushnell and Wolfram (2006) estimate a hazard model for plant retirement and find under certain specifications that plants retire later in non-attainment counties, suggesting that the grandfathered policy retards retirement. List et. al. (2004) use propensity score matching between attainment and non-attainment counties to find that NSR retards modification and retirement. The estimation here improves upon the former methods by adding dynamics and performing structural estimation, along with directly identifying a generator's grandfathered status through its age. However, the estimation here does not exploit county-level differences in attainment status and the resultant differential effects of regulatory policy.

[22] A non-attainment county is one whose air quality fails to meet a certain standard, and thus is bound by stricter regulations.

For the estimation I must choose the functional forms of the model. The production function is $f(v) = {}^{v\text{-}1}$, where represents the depreciated remainder of a generator after one year. This function is normalized so that a generator aged one has a productivity of one. The productivity shock $A$ is idiosyncratic.[23] It is assumed to be multiplicative and distributed log-normally with median one. That fixes its first parameter, $\mu$, to zero, while ${}_A^2$ is estimated. The shock is persistent and evolves according to a Markov process. For simplicity, I allow the transition matrix to be defined by one parameter, $P$. A generator has probability $P$ of having the same productivity shock in the next period. With probability $1 - P$, the next-period productivity shock is randomly chosen from the log-normal distribution.

The adjustment cost parameters $F$ and are left to be estimated. The discount rate is set at 0.95, since the data are annual. Finally, I also estimate the policy variable . Ideally, this could be calibrated from the known policy. Because the complex CAA is modeled simply as an emissions tax, where the value of the tax is the shadow price on pollution that the policy creates, this value is unknown. Hence, it falls into the parameter set to be estimated. Using this procedure, together with the estimates of certain parameters from Table 1.1, I use 1990-2000 data to estimate six parameters: [$F$, , , , ${}_A^2$, $P$].

The estimation results are presented in Table 1.3. The adjustment cost parameter $F$ has no units, so an estimated value of around one does not represent one dollar or one million dollars. Rather, the magnitude has meaning in relation to the function $y_i^i = A_t^i f(v_t^i)(1-\lambda z_t^i) - z_t^i F - \tau_t e_t^i$. The productivity $f(v)$ is normalized so that a generator of age one has an average output of one. Therefore, $F$ taking a value of 2.6 means that the fixed adjustment cost is two-and-a-half times the average annual productivity of a brand new generator. The parameter reflects the fraction of output capacity remaining after one year of depreciation. The estimated value is quite high,

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[23] I have also experimented with adding a common component to the productivity shock to capture real business cycle effects. I used an additional set of moments based on business cycles in the data. However, the common component of the shock was not found to be significant. Another generalization would be to add shocks that are correlated across different generators in the same plant, or owned by the same utility.

more than 99%. This reflects the well-known fact that electric power plants have low depreciation rates and subsequently are kept online for many decades. This exacerbates the perverse effects of grandfathering. The proportional adjustment cost, , is about 0.3, which means that in a period of adjustment 30% of revenue is lost in the adjustment process. This is in addition to the fixed adjustment cost $F$. Like $F$, the policy parameter can be interpreted in relation to the productivity function. The emissions function $g(v)$ is normalized so that emissions are between zero and one, with brand new generators emitting zero and getting dirtier as they age. Therefore, a value of 1.7 means that the implicit tax created by the CAA costs the equivalent of 170% of the productivity of a brand new generator.

**Table 1.3**

| **Estimation Results** | |
|---|---|
| $F$ | 2.624<br>(0.0107) |
| | 0.9975<br>($1.120\times10^{-5}$) |
| | 0.3015<br>(0.000680) |
| | 1.705<br>(0.0145) |
| $^{2}_{A}$ | 0.9523<br>(0.0106) |
| $P$ | 0.5994<br>(0.0038) |

*Notes*: Standard errors are in parentheses. Estimates come from simulated method of moments, matching adjustment moments from Panel A of Table 1.2.

The fact that is significantly different from zero amounts to a rejection of the null hypothesis that grandfathering has no effect on the behavior of plants. Since the implicit tax is paid only by non-grandfathered generators, a significantly positive tax means that these generators respond to an incentive to reduce their emissions which the grandfathered generators do not.

---

Finally, the productivity shocks and the emissions shocks ($B$) could be correlated, though they are independent here.

The parameter $_{A}^{2}$ gives information about the variance of the random productivity shock. The estimated value of the parameter, about 0.95, corresponds to a variance of about 2.5.[24] This parameter is greater than $_{B}^{2}$, the parameter from the lognormal distribution of the error term on the emissions function. This means that the productivity shock is more variable than the emissions shock. Finally, $P$ represents the persistence in the idiosyncratic component of the productivity shock. If $P = 0$, then no persistence exists, and if $P = 1$ then the idiosyncratic component is constant. Here, $P$ is about 0.6. A generator has an 60% chance of staying in its current productivity state and a 40% chance of taking a random draw from the distribution of shocks.

As with most structural estimation models, identification of parameters must be considered. In some GMM estimates, individual parameters can be matched to individual equations, so that it is easy to see what is identifying what. This is not the case here. Instead, a system of equations is used to estimate all of the parameters. However, one can look at how changing individual parameters changes each moment in the simulation. In fact, this is how the standard errors of the estimates are reached. The standard errors being so low suggests that the parameters are well identified.

In Table 1.4, I repeat from Table 1.2 the moments from the data and compare them to the moments that are created by simulating the economy using the estimated parameters, to see how well the model does at matching the moments. The first column of Table 1.4 presents the moments from the data, and the last column presents the simulated moments using the estimated parameters. Though the estimated parameters are matched to the adjustment fraction moments from Panel A of Table 1.2, Table 1.4 also presents the simulated values of the annual moments from Panel B of Table 1.2, to show how the estimated results predict moments outside of the set used in the estimation. For reasons of space, I only present the annual moments from years 1995 and 2000, instead of all ten years. The adjustment fraction moments are matched closely with the estimates, but the annual moments from the simulation indicate younger generators and fewer grandfathered generators. The fact that the estimates cannot perfectly match the data suggests that simulations under those parameters lead to more generators adjusting

[24] The variance of a lognormal distribution is $\exp(^{2} - 1) \times \exp(2\mu + ^{2})$, and here $\mu$ is zero.

than actually do in the data. Thus, simulation results below may underestimate the effects of grandfathering.

**Table 1.4**

| **Comparing Actual and Simulated Moments** | | |
|---|---|---|
| | Data (from Table 1.2) | Estimate |
| *Adjustment Moments* | | |
| Percent Adjusting Aged 1-10 | 1.25 | 0.89 |
| Percent Adjusting Aged 11-20 | 1.44 | 0.95 |
| Percent Adjusting Aged 21-25, Grandfathered | 0.90 | 0.79 |
| Percent Adjusting Aged 21-25, Non-Grandfathered | 1.28 | 0.91 |
| Percent Adjusting Aged 26-30, Grandfathered | 2.46 | 1.09 |
| Percent Adjusting Aged 26-30, Non-Grandfathered | 5.25 | 5.46 |
| Percent Adjusting Aged 31-40 | 2.72 | 1.07 |
| Percent Adjusting Aged 40 or older | 3.37 | 3.53 |
| *Annual Moments (1995 and 2000 only)* | | |
| Mean Age 1995 | 35.636 | 28.578 |
| Mean Age 2000 | 36.313 | 30.001 |
| Fraction Grandfathered 1995 | 0.695 | 0.5200 |
| Fraction Grandfathered 2000 | 0.616 | 0.4698 |

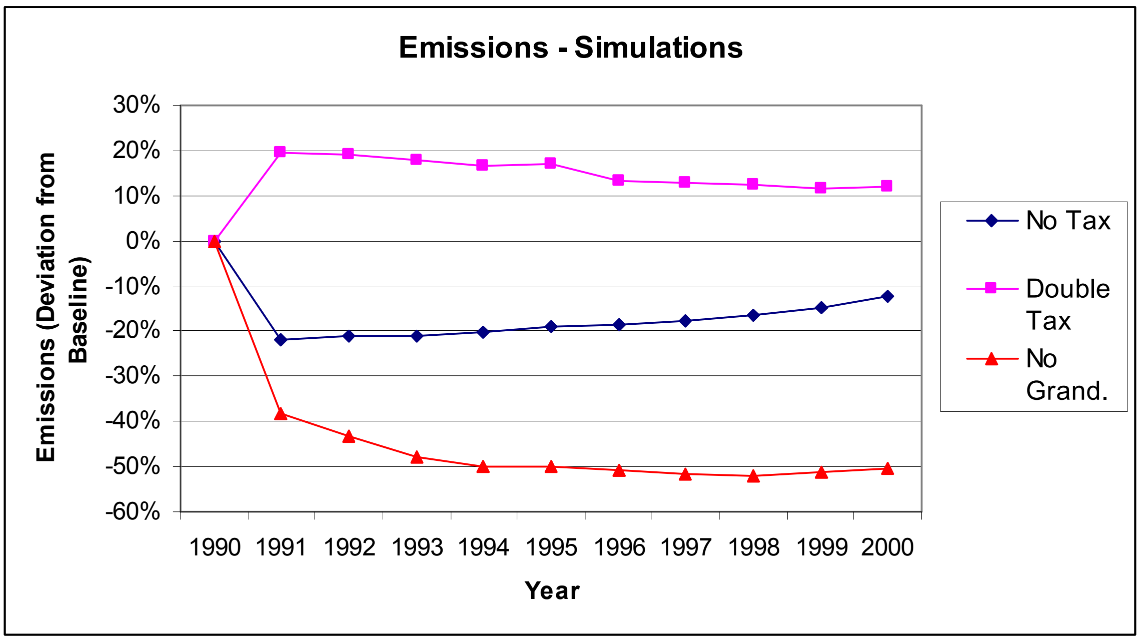
*Notes*: Simulated moments are taken from parameter estimates in Table 1.3.

## 1.4. Counterfactual Simulations

Finally, I use the estimated parameters to simulate the economic effects of policy changes. Specifically, I consider the impact of grandfathering in the CAA by comparing a baseline simulation using the estimated parameters to three counterfactual simulations (of the ten years of the economy for which I have data). In the first counterfactual, I keep all parameters the same, except that I eliminate any grandfathering provisions starting in the first year. This simulation represents what would happen if the government had decided in 1990 to eliminate the grandfathered status for plants. Next, I set the implicit tax rate on pollution equal to zero, to simulate what would have happened had the CAA been repealed in 1990. Finally, the third counterfactual keeps the grandfathering provisions but doubles the implicit tax rate on pollution. This represents the CAA regulations being doubled in strength in 1990.[25]

For the eleven periods of the three counterfactual simulations, Figure 1.2 presents the level of pollution intensity and Figure 1.3 shows the fraction of generators that adjust in each period. Both figures plot the proportional deviation from the baseline for each counterfactual simulation. The line "No Grand." represents the simulation that eliminates grandfathering. The line "No Tax" represents the simulation with the tax rate changed to zero (where grandfathering becomes irrelevant). The line "Double Tax" represents the simulation with an implicit tax rate raised to twice the estimated rate.

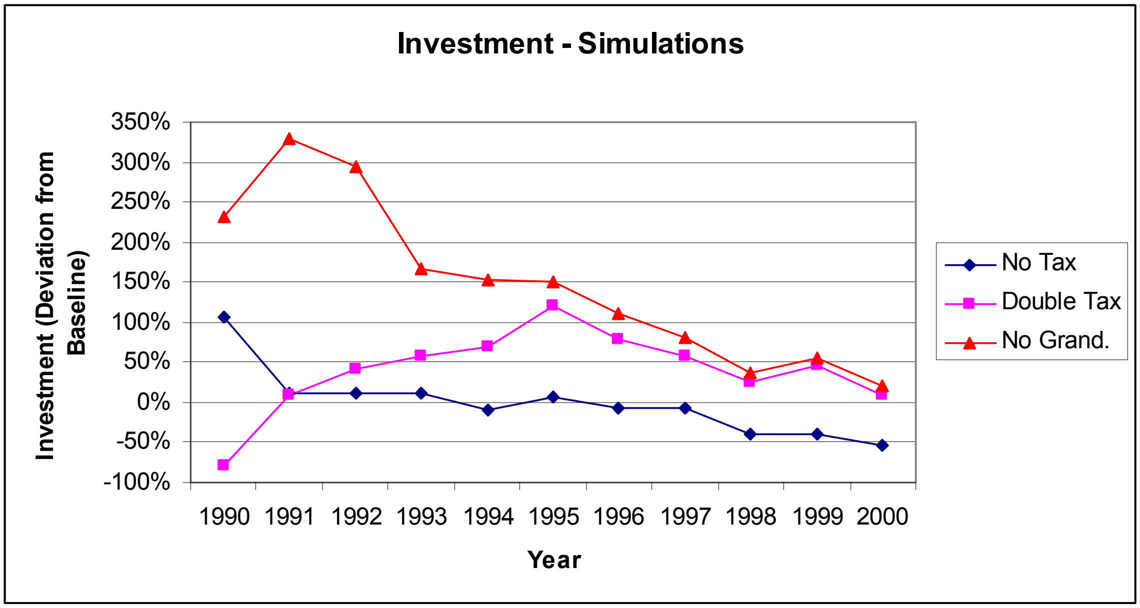
**Figure 1.2**




[25] These are not the only counterfactual policy experiments that could be simulated with the model. For example, one policy to counteract the perverse effects of the grandfathering is to provide direct monetary incentives to investment. This could be modeled by an exogenous policy variable that affects the fixed cost $F$ of investing. This policy might be more politically feasible then a removal of grandfathering. Alternatively, the policy could gradually phase-out the grandfathering status for older plants, or end it after a certain age of plants. Additionally, I assume that all of the costs of the policy are described by the implicit tax . However, these cover only marginal costs of the CAA (for example, the higher per-unit costs of cleaner-burning coal). Other costs may be fixed and be a part of $F$, which I am interpreting as the technology-based, not policy-based, adjustment costs. Therefore, since my policy counterfactuals only change , they only capture a change in the marginal costs of the policy, and may understate the overall effect of the CAA.

*Notes:* Y-axis is the proportional deviation of emissions quantity from baseline simulation. "No Tax" is simulation run without an emissions tax. "Double Tax" is simulation run with emissions tax = twice the estimated parameter. "No Gran" is simulation with grandfathering eliminated; all plants are subject to the environmental tax.

**Figure 1.3**




*Notes:* Investment is the fraction of plants that adjust in that year. The y-axis is the proportional deviation of investment from baseline simulation. "No Tax" is simulation run without an emissions tax. "Double Tax" is simulation run with emissions tax = twice the estimated parameter. "No Gran" is simulation with grandfathering eliminated; all plants are subject to the environmental tax.

Consider first the "No Grand." simulation, which shows the largest difference from the baseline emissions levels. In Figure 1.2, emissions levels drop sharply. Since older generators are no longer grandfathered under this counterfactual policy simulation, those generators now face an emissions tax. Many of these older generators now choose to adjust their capital to a new vintage to reduce their emissions, especially since they have delayed productivity-enhancing upgrades to avoid that tax. In the next year, many more generators are newer and cleaner. This can also be seen in the "No Grand." curve in Figure 1.3: once the law is changed, the rate of investment is much higher due to the shock in the policy. Though the fraction adjusting eventually gets closer to the baseline levels, the initial increase in brand new generators reduces emissions throughout the simulation period.

Since the productivity function is estimated, these simulation results can be used to compare average productivity under the baseline simulation to that under "No Grand." The age and simulated productivity shock $A$ of each generator give the productivity $Af(v)$. Averaging this productivity over each generator and over all ten years for both the baseline and the "No Grand." simulation, I find that productivity under the baseline is about 3% less than under "No Grand." Similarly, in 2000 the emissions intensity under the baseline simulation is about 78% greater than that under "No Grand."[26] The average generator age in the baseline simulation in 2000 is 30.00 years. In the "No Grand." simulation, this average is only 15.04 years. These results are of a larger magnitude than those in Nelson et. al. (1993), who find that regulation increased generator age by 24.6% over the period 1969-1983. However, the comparison between the baseline and "No Grand." simulations is not identical to the effect found in that paper. There, the authors show how the addition of the grandfathered policy increased plant ages. Here, I show how a counterfactual removal of grandfathered provisions would have decreased ages. The result I find is almost identical to that of Biewald et. al. (1998), who find that if all plants were subject to NSR standards (that is, if grandfathering were eliminated), then emissions of $SO_2$ and $NO_X$ would fall by 75%.

The results from the "No Tax" simulation are in the same direction as those in the "No Grand." simulation, since it effectively removes any benefit of grandfathering. With this repeal of the tax on emissions, new investment spikes early, causing a *decrease* in emissions for at least the next ten years. This is due to the different responses of generators that are initially grandfathered and those that are not. For generators not initially grandfathered, eliminating the environmental policy means that older capital is less costly, so they are less likely to update. This increases emissions and lowers investment compared to the baseline. But consider the response of generators that were initially grandfathered. Under the baseline grandfathered policy, they have an extra

[26] Standard errors for these estimates of the impact of grandfathering on productivity and emissions can be reached using Monte Carlo methods, though this is still work in progress. From the SMM estimation, I have the covariance matrix of the parameter estimates. I generate 1000 realizations of the parameter set generated from the estimated distribution. For each set of parameters, I evaluate the baseline simulation

disincentive to update, since in doing so they would lose their valuable grandfathered status. Doing away with the policy does away with that valuable status and their disincentive to adjust. Hence, grandfathered generators are *more* likely to adjust after elimination of the emissions tax. Under the simulations shown in Figures 1.2 and 1.3, the response of the grandfathered generators dominates, and emissions decrease with a repeal of environmental policy compared to the baseline.

This can be seen from Figure 1.4, which plots separately the response of grandfathered and non-grandfathered generators to the "No Tax" and "Double Tax" policy changes, along with the baseline. The top three curves represent the emissions from the generators that were initially grandfathered at the beginning of the simulation, and the bottom three curves (two are coincidental for the first seven periods of the simulation) represent the emissions from generators initially not grandfathered. The value of emissions is normalized to the average level under the baseline in 1990. For the grandfathered generators, the response to a change in policy is perverse: when the tax is doubled, emissions go up, and when the tax is eliminated emissions fall. For non-grandfathered generators, the results are not perverse: doubling the tax reduces emissions and eliminating the tax increases emissions. However, this last response only shows up in the last few periods of the simulation. Until then, the baseline and "No Tax" simulations are identical for non-grandfathered generators. Because many of these generators are sufficiently young, the policy even at the baseline level had no effect on their investment decision. Thus, eliminating the policy has no change, until the generators are old enough for it to matter. Figure 1.4 demonstrates that the perverse effect comes only from those generators that are grandfathered, and hence the magnitude and even the existence of a perverse effect overall depends on the fraction of the fleet which is grandfathered at the onset of the policy change.

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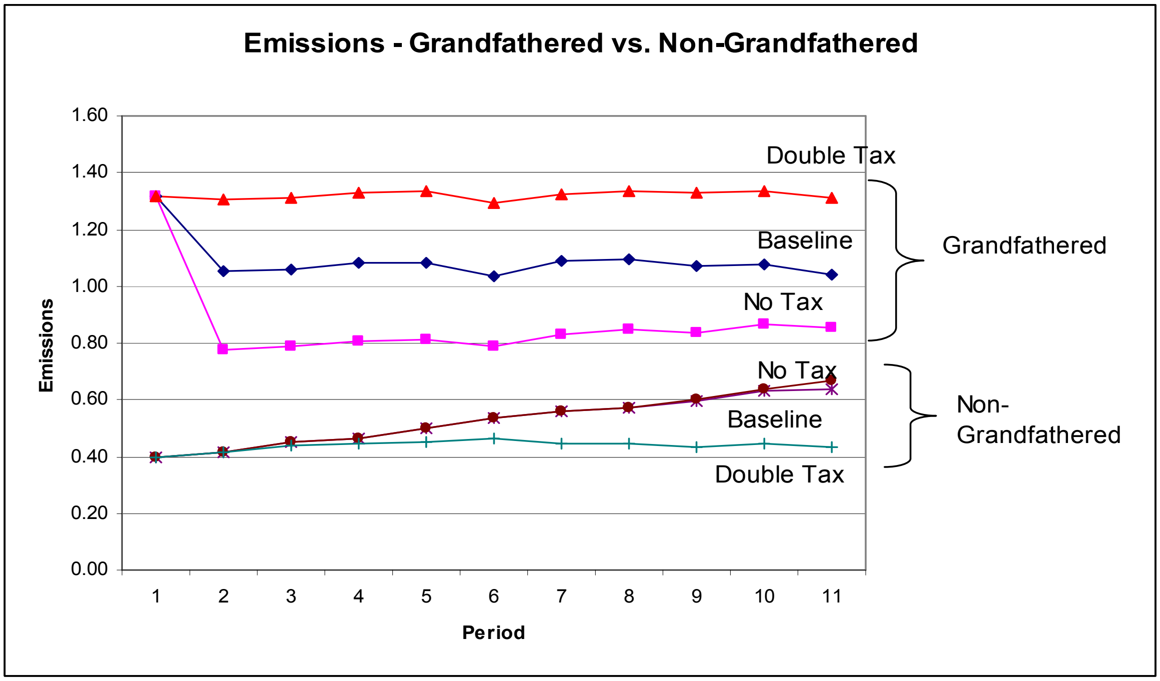
and all three counterfactuals. The distribution of any simulated outcome (e.g., the emissions in each year) can thus be reached, and standard errors for the simulations follow.

**Figure 1.4**




*Notes*: The Y-axis is the level of emissions, normalized to the average initial level in the baseline simulation. "No Tax" is simulation run with repeal of the emissions tax. "Double Tax" is simulation run with emissions tax doubled.

These results conform to previous theoretical and empirical findings of a perverse effect of grandfathered policies. In Gruenspecht (1982), it is found that strengthening the emissions standards of new cars has a perverse effect: total automobile emissions rise in the short term. This is because the stricter standards apply only to the new cars, which effectively grandfathers the existing cars. New cars are thus made more expensive, and consumers retain their old cars longer. This increases the average age of the vehicle fleet, which increases emissions. In the long run, after all of the old cars have been scrapped, the policy has the desired effect of decreasing emissions.[27] This perverse effect of a grandfathered standard can be called the "Gruenspecht effect." While in that original paper, it was a tightening of the standards that created a perverse effect, here I find that loosening the standards (in fact, eliminating the policy) creates a similar perverse effect but in the opposite direction: emissions decrease. Though consistent with Gruenspecht

[27] Further evidence of the perverse effect of increasing emissions standards or fuel economy standards can be found in Stavins (2005) and Parry et.al. (2004).

(1982), this result contrasts with Nelson et. al. (1993), who do not find evidence of a Gruenspecht effect. They find that in the absence of regulations, emissions from electric power plants would have increased by 34.6%.

The results from "Double Tax" are qualitatively the opposite of those from "No Tax," and the magnitudes of the changes in emissions are about the same. This is because both grandfathered generators and non-grandfathered generators react in the opposite way under "Double Tax" as they do under "No Tax." Thus, a strengthening of the policy leads to an increase in emissions for the next ten years. Maloney and Brady (1988) find the same effect with a similar magnitude. They find that a doubling of pollution regulation has about an eight percent increase in emissions (though their data on power plants come from 1974-1979). As Figure 1.2 shows, a doubling of the virtual tax in 1990 leads to about a 12% increase in emissions in 2000.

An increase in emissions following a policy change does not necessarily indicate that the policy change is welfare reducing. The policy change may induce some other welfare-increasing behavior, like investment in new, more efficient plants, which could offset the environmental costs. A complete welfare analysis requires a specification of the social welfare function. Without that, though, I can at least investigate how these policy changes impact social welfare from environmental and non-environmental sources. The total non-environmental social welfare function from the industry studied is the discounted sum of revenues minus costs, not counting the virtual environmental tax, which is a transfer.[28] That equals $\sum_{t=1}^{T}\beta^{t-1}\{\sum_{i=1}^{N}A_t^i f(v_t^i)(1-\lambda z_t^i)-Fz_t^i\}$. The environmental social welfare is a function of the total emissions level. For now, suppose that the costs to welfare are proportional to the level of emissions: $-\sum_{t=1}^{T}\beta^{t-1}\{\sum_{i=1}^{N}\Omega B_t^i g(v_t^i)\}$, where is a constant. Using the simulations for the baseline

[28] Since the virtual tax models command and control mandates (e.g. requiring scrubbers), it might be appropriate to count the cost of the virtual tax as a deadweight loss rather than a transfer. It is likely to fall somewhere in between. By counting it as a transfer, this potentially understates the welfare costs when older plants refrain from adjusting and choose to pay more in emissions taxes.

and three counterfactual policies, I evaluate these social welfare expressions. I then compare the values in the counterfactual simulations to those in the baseline simulation.

Table 1.5 presents the proportional difference between welfare in each counterfactual simulation and welfare in the baseline simulation, for each of the two categories of welfare. For example, the welfare from non-environmental sources is 1.1% lower in the "No Tax" simulation than in the baseline. The direction of the change in environmental welfare is also apparent from Figure 1.2: when emissions rise, environmental welfare falls. It also holds that welfare from the two sources, environmental and non-environmental, move in opposite directions. This is because when more old generators are adjusting, as in the "No Tax" and "No Grand." simulations, the benefits from their additional productivity are outweighed by the adjustment costs, given that in this simulation the benefits are only summed up over eleven years, not the entire life of the plant. More importantly, the proportional changes in environmental welfare are much larger that those in non-environmental welfare. While the effect of the policy on non-environmental areas of the economy may outweigh its effect on the environment, the results here indicate that is unlikely.

**Table 1.5**

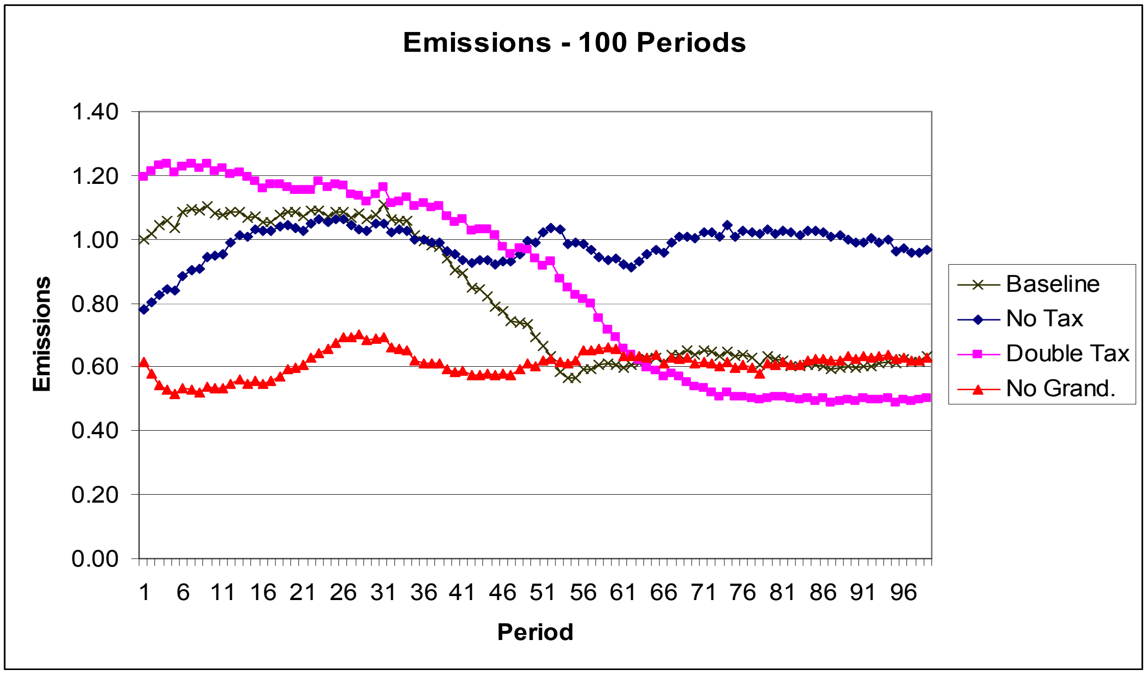
| **Welfare Analysis** | | |
|---|---|---|
| | Non-environmental welfare | Environmental welfare |
| No Tax | –0.01137 | 0.1622 |
| Double Tax | 0.0001823 | –0.1356 |
| No Grand. | –0.06643 | 0.4197 |

*Notes*: The values in the table are the proportional differences in social welfare outcomes in two categories between the listed counterfactual simulation and the baseline simulation. The simulations are run for eleven years (1990-2000) and discounted annually with a discount factor of 0.95.

One might also consider a cost-effectiveness-type analysis of grandfathering. That is, if grandfathering is eliminated and the level of the virtual tax changed, can the same level of emissions as the baseline be obtained? It turns out that the answer is no: regardless of how high or low the virtual tax is made, if grandfathering is eliminated emissions will always be lower than in the baseline simulation. Note that the "No Tax" curve in Figure 1.2 is below the x-axis, so that emissions are lower when the policy is repealed than in the baseline. Consider another simulation where there is neither a virtual tax nor grandfathering. This simulation is actually identical to the "No Tax" simulation, since once the virtual tax is eliminated, it is irrelevant whether or not there is grandfathering. If grandfathering is eliminated and the tax rate is kept the same, this is the "No Grand." simulation shown in Figure 1.2, and emissions are lower than in the baseline. If grandfathering is eliminated and the tax rate is also eliminated, this is the "No Tax" simulation, and emissions are also lower than in the baseline. If grandfathering is eliminated and the tax rate is increased, then emissions would be lower still than in the "No Grand." simulation, since a higher tax makes grandfathered plants even less likely to adjust. Therefore, without grandfathering emissions must be lower than the baseline. It is impossible to achieve the same outcome as the baseline by altering the tax rate and eliminating grandfathering.

These effects pertain to the short run only. In the long run, a different set of outcomes is likely since all generators eventually adjust at least once and therefore lose their grandfathered status. Figure 1.5 extends the simulations through 100 periods and presents the average emissions intensity in each year for each counterfactual simulation as well as the baseline, normalized to the initial level of emissions in the baseline. Clearly, this model cannot be expected reliably to predict the behavior of the power generating industry 100 years into the future. By extending the simulation out to the long run, however, the nature of the effects of grandfathering become clearer.

**Figure 1.5**




*Notes:* Y-axis is the level of emissions normalized to the initial level in the baseline simulation. "No Tax" is simulation run with repeal of the emissions tax. "Double Tax" is simulation run with emissions tax doubled. "No Grand." is simulation with grandfathering eliminated; all plants become subject to the environmental tax.

In the baseline simulation, emissions begin to drop significantly at around period 35. This is because eventually the grandfathered generators adjust and lose their grandfathered status. Afterwards, they then retire earlier than they would have if they were still grandfathered, resulting in a generally younger fleet and reduced emissions. The "No Grand." simulation emissions are initially lower than the baseline (for over 50 years, not just for the ten years shown in Figure 1.2). They then approach the baseline simulation by the last periods. The "No Grand." simulation has the same tax rate as the baseline but eliminates the grandfathering of generators. By the last period, though, even in the baseline simulation all generators have adjusted at least once. After all generators have lost their grandfathered status, there is no difference between the baseline and "No Grand." policies, hence they converge.

The comparison between the "No Tax" and "Double Tax" counterfactual simulations relative to the baseline simulation most clearly demonstrates the short term and long term effects of grandfathered policies. In the "No Tax" (repeal) simulation, overall emissions are lower than in the baseline simulation for the first 35 periods. After that, "No Tax" emissions become about two-thirds higher than baseline emissions. The Gruenspecht effect of changing the policy is short term, and in the long run the desired effect of environmental policy does indeed materialize: removing an emissions policy leads to higher long run emissions. Similarly, the emissions under a doubling of the environmental tax exceed those under the baseline for the first 65 years of the simulation. Only after 65 years do the perverse effects of grandfathering disappear, and emissions end up about 21% lower than in the baseline. Figure 1.4 thus shows how long the "short run" is, and thus how long the perverse effects of grandfathering can last.

The results from these simulations potentially have important policy implications. While the Gruenspecht effect is generally thought to be a short term effect, it is relevant to the overall performance of an environmental policy like the CAA. The short term perverse effect from strengthening a grandfathered environmental regulation can dominate the long term environmental benefit for some combination of three reasons: if the short term is sufficiently long, if the discount factor in social welfare is sufficiently high, or if damages from emissions are sufficiently convex to make short-term spikes in emissions very costly.

All three of these reasons for the long term to be dominated by the short term effect are likely to exist in this industry. First, electric power is an industry with a long short term, due to the long lifespan of generating plants. As seen from Figure 1.4, the short term lasts for almost half of a century. When society discounts the future, the benefits of a long run improvement in environmental quality are outweighed by the costs of the short run degradation of environmental quality. Second, even if plants are not so long-lived, a sufficiently high discount rate can always make the perverse short-run outweigh the long-run gains. Third, we do indeed have evidence that damages from emissions are convex.[29]

It may be useful to distinguish two separate perverse effects from grandfathered environmental policy. The first, which can be called the "weak Gruenspecht effect," is the familiar result that strengthening a grandfathered policy has short term perverse effects: if the tax is doubled, then emissions initially rise. I find here that the same effect works in the opposite direction: if the tax is eliminated, then emissions fall. The weak Gruenspecht effect applies only to grandfathered plants, so that a sufficient number of non-grandfathered plants in the fleet can mean that the perverse effects may not be realized overall.

The "strong Gruenspecht effect" can be defined to occur when the costs of the perverse short term effect outweigh the benefits of the long term outcome – for any combination of the reasons listed above. Since emissions after the CAA is repealed ("No Tax") are less than baseline emission for 40 years, for example, it is possible that total discounted environmental damages are less without the CAA than with it. If this is true, then the strong Gruenspecht effect holds. Whether the strong Gruenspecht effect holds depends on both the social discount factor and the shape of the damage function. If the strong Gruenspecht effect holds in this case, it implies an important policy prescription: to reduce total discounted environmental damages, we should weaken or repeal the regulations in the CAA.

To investigate the existence of a strong Gruenspecht effect, Table 1.6 presents back-of-the-envelope calculations for total discounted environmental damages under various assumptions about the social discount rate and the concavity of the damage function from emissions. For each set of assumptions, I calculate the ratio of total discounted environmental damages under the baseline simulations to total discounted environmental damages under the "No Tax" simulation. If this ratio is greater than one, then the strong Gruenspecht effect holds, since eliminating the (grandfathered) policy actually decreases damages from emissions.

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[29] Khanna (2000, Figure 1) and EPA (1997).

**Table 1.6**

| **Total Discounted Environmental Damages** | |
|---|---|
| Linear Environmental Damages | |
| $\beta_s$ | Damages Baseline/Damages "No Tax" |
| 0.9 | 1.1429 |
| 0.95 | 1.0629 |
| 0.9686 | 1 |
| 0.99 | 0.8863 |
| Nonlinear Environmental Damages ($e^{\zeta}$, $\beta_s$ = 0.9686) | |
| $\zeta$ | Damages Baseline/Damages "No Tax" |
| 0.5 | 0.9961 |
| 1 | 1 |
| 1.5 | 1.0096 |
| 2 | 1.0245 |
| 2.5 | 1.0429 |

*Notes:* Simulations are run for 100 periods and damages are discounted and totaled over those periods. Simulations are run with parameters in Table 1.3. Right hand column presents the ratio of total discounted environmental damages in baseline simulation to total discounted environmental damages in "No Tax" simulation. Thus, when this ratio exceeds one, the "strong Gruenspecht effect" holds. Under linear environmental damages, $\zeta$ is fixed at 1. Under nonlinear environmental damages, $\beta_s$ is fixed at 0.9686.

Table 1.6 shows how varying two important parameters affects the existence of this effect. In the top half of Table 1.6, I vary the social discount rate $\beta_s$, and I keep environmental damages linear. That is, total environmental damages over the period is $\sum_{i=1}^{100} \beta_s{}^t e_t$, where $e_t$ is the emission intensity in period $t$. I calculate damages over the 100 periods in the simulations from Figure 1.5. When $\beta_s$ is 0.9 or 0.95, the ratio in the table is greater than one, indicating that the strong Gruenspecht effect holds. At a higher $\beta_s$ of 0.99, the effect does not hold. Since a higher $\beta_s$ means that society discounts the future less, the years in the future count more towards utility than they do in the other rows in the table. The threshold level of $\beta_s$, where total environmental damages are just equal under each of the two policies, is 0.9686. Thus, even without convex damages, a discount rate of 4% or more yields a strong Gruenspecht effect.

The second half of Table 1.6 varies the convexity of the damage function from emissions while holding $\beta_s$ at its threshold value of 0.9686 throughout. The parameter $\zeta$ measures that convexity, where total damages from emissions equal $\sum_{i=1}^{100} \beta_s{}^t e_t{}^{\zeta}$. When

= 1, this is the linear case in the first half of the table. When is greater than one, damages are convex. Under these parameters, the strong Gruenspecht effect holds whenever damages are convex, since the ratio presented is greater than one. Furthermore, as the damage function gets more convex ( gets larger), the perverse effect gets larger. In all simulations, emission levels are higher overall during the earlier periods than the later periods, as can be seen in Figure 1.5. Thus, a more convex damage function means that emissions levels in the earlier periods count more than in the later periods. Since the perverse effects are concentrated in the earlier periods, it follows that a more convex damage function leads to a higher likelihood of a strong Gruenspecht effect.

**1.5. Conclusion**

This paper investigates how environmental regulations impact plant investment decisions and plant emissions. Regulations that are grandfathered can have short-term perverse effects. When grandfathered regulations are strengthened, emissions can increase in the short run, as grandfathered plants avoid being subject to the regulation by withholding investment in newer, cleaner technologies. Also, when grandfathered regulations are weakened, emissions can decrease in the short run, as grandfathered plants lose their valuable status that keeps them from investing. For electric power plants subject to the Clean Air Act, I find that ten years is still the short term. Removing the grandfathering from the CAA in 1990 leads to a 50% decrease in emissions intensity by 2000.

The analysis here suggests that introducing a grandfathered environmental regulation makes the environment worse off, at least in the short run. However, evidence from the CAA disputes that; total domestic emissions of sulfur dioxide, carbon monoxide, and volatile organic compounds all began to decrease abruptly in 1970, the year that the CAA was passed (Brock and Taylor 2004). It should thus be emphasized that this paper is studying only the policies of the CAA insofar as they are grandfathered. Section 111, which contains the NSR provisions, is only a part of the entire law, and many of the other regulations are not grandfathered. Because of these other aspects of the law, the CAA reduced emissions immediately after going into effect. The results in this paper indicate that emissions would have been reduced even more had grandfathering not been a part of the law.

The model makes a number of simplifying assumptions that can be relaxed to refine the results. In the model, investment only occurs on the extensive margin: plants make a binary decision about whether or not to adjust. One could allow for investment on the intensive margin, that is, a continuous level of investment. Or, keeping a discrete choice approach, one could allow for the choice of type of plant (coal, nuclear, or other fuel). Both of these extensions point to a possible caveat of the model: utilities are not able to separately choose their plants' productivity and emissions. Both are jointly determined by the age of the plant (along with random technology shocks). This eliminates the possibility that plants of the same vintage may differ in their pollution intensity or productivity depending on technology. Because the model here does not capture these decisions that utilities can make, the results may be biased. For example, in the counterfactual simulation where the CAA is eliminated, if utilities could build new power plants which are more productive but not less polluting than older plants, then the perverse Gruenspecht I find from the policy elimination may be lessened. This bias could go in the opposite direction as well, if some utilities build new plants that are less productive and less polluting than other new plants. While it is arguable that the magnitude of this bias is small, since newer plants do tend to be more productive and less polluting, the bias cannot be avoided unless the model expands the plant's choice set beyond a binary decision.

The paper can also be extended by changing how the emissions policy is modeled. The policy is defined as a virtual tax, reflecting the shadow price of the regulation. However, different types of mandates can have different effects not captured by modeling all mandates as a tax.[30] The policy here is constant and without uncertainty. Adding uncertainty about the policy to the plants' decisions may allow the model to match the data more accurately. Alternative policies can also be considered within this model. For

[30] See Helfand (1991) and Chapter 2 of this dissertation.

example, to counteract the investment disincentive created by grandfathering, regulators could provide direct subsidies to investment.[31]

The short term or potentially present-value perverse effects need to be incorporated into any analysis of the impact of a change in a grandfathered regulation. This is especially true of regulations that apply to electric power plants, which are long-lived and subsequently have a longer "short term." If an environmental regulation like the CAA is weakened, we expect a short term decrease in emissions from grandfathered plants. Only in the long term, once all plants have lost their initial grandfathered status, would the environment be worse off. The short term improvement in the environment may look like evidence of a "win-win" situation regarding reform of the policy. Yet such an analysis would need to balance the long term and short term effects of the policy change.

[31] With a stochastic scrapping subsidy, the model is similar to that in Adda and Cooper (2000).

## Chapter 2: "The General Equilibrium Incidence of Environmental Mandates"

Much literature compares the efficiency properties of environmental policies, generally finding that incentives like taxes or permits are more cost-effective than mandates – at least in the case where firms are heterogeneous and government cannot know how to tailor mandates to each firm. In contrast, the literature on the distributional effects of such policies is limited. Some papers identify the demographic characteristics or locations of households in jurisdictions that are differentially affected by environmental protection, while others look at the burdens on households that buy products made more expensive by environmental protection.[32] All of these papers ignore effects of environmental policies on the wage rate and the return to capital – both of which also affect real incomes. Yet, restrictive command and control (CAC) regulations can simultaneously affect both the product prices and factor prices.

Of course, the public economics literature since Harberger (1962) is replete with general equilibrium studies of the incidence of taxation. A few such papers look at the incidence of environmental taxes, where the question is about how the revenue burden is distributed. No such literature looks at mandates, perhaps implicitly because mandates do not have revenue whose burden can be distributed.[33] Yet CAC mandates clearly interfere with firms' decisions about use of labor, use of capital, the amount to produce, and the price to charge. We therefore find it surprising that we cannot find in the literature any general equilibrium model of the incidence of non-revenue-raising environmental regulations, with simultaneous effects on the uses side of income (product prices) and sources side of income (factor prices).

To begin such a literature, this paper starts with rudimentary models in the style of Harberger (1962), with two competitive sectors and constant returns to scale, but we

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[32] Examples of papers in the first category include Becker (2004) or Sieg et al (2005). Examples in the second category include Gianessi and Peskin (1980), Robison (1985), Metcalf (1999), or West and Williams (2004).

[33] The incidence of a pollution tax is studied by e.g. Bovenberg and Goulder (1997), Chua (2003), and Fullerton and Heutel (2007). The effect of a pollution mandate on factor prices is studied by Das (2004) in a trade model with fixed world output prices. We find both factor prices and output prices in a closed economy for several different kinds of mandates, but certainly results would be different in open economy.

add the important complication that the "dirty" sector uses three inputs to production: labor, capital, and pollution. Thus, any two of these inputs can be complements or substitutes. The "clean" sector uses only labor and capital, which are in fixed supply but perfectly mobile between sectors. We then solve models representing four types of non-revenue-raising policies: the handout of pollution permits, a restriction on the "absolute" quantity of pollution, a "relative" standard on pollution per unit of output, and a relative standard on pollution per unit of an input (such as capital).

A key to understanding results from these models is that the first two kinds of regulations restrict the amount of pollution, and so create scarcity rents. The rights to these scarcity rents may be fairly obvious: gains accrue to whatever entity is handed the permits or the rights to the restricted quantity of pollution. To cover the higher shadow price of pollution, however, the product price must rise more than in the other two cases. These policies also may reduce the return to either labor or capital, whichever is a relative complement to pollution or whichever is used intensively in the polluting sector. We start with those models and policies because they are fairly easy to understand.

The more interesting results here pertain to the "relative" standards. In one case, the firm can acquire more of the valuable pollution rights only if it produces more output, and so it may raise demands for either or both inputs (relative to the absolute quantity restriction). Production does not shrink as much, and the output price does not rise to cover the cost of paying for scarcity rents. In fact, output price can fall. This policy can easily distribute gains to some kinds of individuals, but it shifts production and imposes costs on others. The restriction on pollution per unit of capital implies that firms acquire pollution rights only by using more capital, which tends to raise the demand for capital and its return. But this policy also raises costs and reduces output, which tends to reduce demand for capital if the sector is capital intensive. Thus the return to capital can rise or fall, even if the dirty sector is capital intensive. Finally, if the return to capital falls and the dirty sector is capital intensive, then the overall cost of production can fall, so that a tighter environmental restriction reduces the price of the dirty good.

Thus, we see that some standard principles of tax incidence are at play, but some other effects specific to mandates are introduced. Section 2.1 below summarizes the importance of such mandates in actual policymaking, and it reviews the literature that has studied them. Section 2.2 then introduces the simplest version of our model, for pollution permits. Section 2.3 looks at absolute quantity standards. Sections 2.4 and 2.5 present the main contributions of our paper. Section 2.4 models a restriction on pollution per unit of output, and section 2.5 models pollution per unit input. Section 2.6 offers concluding remarks.

## 2.1. Review of Environmental Mandates and Modeling

Especially in the earlier years of their existence, environmental regulations have most often been command-and-control (CAC) or technology mandates rather than incentives like pollution taxes or tradable permits. Those mandates, though, can take many forms for different industries.[34] The Clean Air Act Amendments (CAAA) set national ambient air quality standards, and jurisdictions that do not meet these standards are forced to create individual implementation plans. These plans often differ greatly from each other. Modeling the Clean Air Act as a single limit on emissions is difficult, except perhaps for the national emissions standards for new facilities under the New Source Performance Standards of the 1970 CAAA. Like the NPDES water standards these air pollution regulations are technology-based, that is, determined by the current state of abatement technology.

Systems of tradable emissions permits are becoming more popular, including the 1990 CAAA's national market for sulfur dioxide ($SO_2$) emissions, the market in the northeast for nitrogen oxide ($NO_x$) emissions, the South Coast Air Quality Management District permit system for $SO_2$ and $NO_x$ emissions in the Los Angeles area launched in January 1994, and the seven states that have established emissions credit programs for $NO_x$ and volatile organic compounds (VOC) since 1989 under the EPA's emissions trading program framework. These tradable emissions permits may achieve the same net

[34] Historically, the Water Quality Act of 1965 was the first national policy to allow states to determine maximum discharge limits for various pollutants and to allocate (nontradable) permits to polluters to reach that goal. The National Pollution Discharge Emissions System (NPDES) of the Federal Water Pollution Control Act of 1972 imposes effluent standards on water emissions, and it gives polluters the freedom to choose the technology they want to use to achieve those standards.

level of environmental benefits as technology mandates, and perhaps more cheaply, but they have important distributional differences.

Finally, emissions standards may be relative rather than absolute. A policy may mandate the maximum emissions per unit output, or per unit of some input like a particular chemical or oil. These policies may be seen as more reasonable than an absolute limit per firm, especially when applied to firms of various sizes. A regulator would not expect a large firm to reach the same level of emissions as a small firm. By enacting a relative policy, the regulator can avoid deciding on a specific allocation of allowed emissions levels. Because of the variety of environmental mandates under different state implementation plans, it is difficult to pinpoint what policies have this relative form. In a 1982 survey of regulators administered by Resources for the Future, however, 97% of air pollution regulating agencies and 100% of water pollution regulating agencies said they use limits on emissions per unit of some input, and 70% of air and 50% of water agencies said they use limits on emissions per unit output (Russell et al 1986, p. 19). Such large proportions suggest modeling some environmental policies as limits on ratios of pollution to output or to an input.

Current federal environmental regulations are quite complex. The Code of Federal Regulations Title 40 lists hundreds of rules that apply to various emitters and industries, and most states have their own sets of regulations. Some mandates are described in terms of emissions per unit output, such as the VOC standard for automobile refinish coatings that is stated in terms of grams per liter of coating. For new plants that produce sulfuric acid, the emissions standard for $SO_2$ is 2 kg per metric ton of acid produced.[35] The Texas Commission for Environmental Quality sets standards for municipal hazardous waste generators that are based on the amount of output produced.[36] The state of New York sets limits on fluoride emissions per unit output from aluminum reduction plants.[37] Mandates also take the form of emissions per unit of some input. The federal standard for particulate matter emissions for fossil-fuel-fired steam generators is

[35] Code of Federal Regulations, Title 40, Chapter 1, §60.82.
[36] Texas Administrative Code, Title 30, Section 1, §335.69.
[37] New York Environmental Conservation Rules and Regulations §209.2.

43 nanograms per joule of heat input derived from fossil fuel or wood residue.[38] Other standards are stated in terms of emissions per unit heat input in Texas for electric generators and solid fossil-fuel fired steam generators.[39] Finally, even for a particular industry, emissions standards can differ based on the technology employed. Phosphoric acid manufacturing plants, for example, face standards for fluorides and particulate matter that depend on the production technology of the plant.[40] Emissions rates for iron and steel processes in New York depend on the technology.[41] Limits on $SO_2$ emissions for oil and gas producers in Texas are 25 tons/year *per facility*.[42] Standards per facility also apply in New York for petroleum refineries.[43]

International regulations also show evidence of similar relative standards. In the European carbon permit market, some allocation mechanisms that have been proposed are based on the historical output of firms (Bohringer and Lange 2005). Agricultural regulations can be a limit on the amount of nitrogen per hectare of land.

We cannot incorporate all of these different types of mandates in a single model with clear analytical results. We can, however, model a few types of mandates and compare results, to see their differential impacts on the distribution of costs. For example, we model technology mandates and per facility standards as limits on the amount of pollution per unit capital.

In the economics literature, environmental mandates are typically modeled as limits on the amount of pollution emitted, though most mandates actually take other forms.[44] The most exhaustive theoretical analysis of different types of environmental

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[38] Code of Federal Regulations, Title 40, Chapter 1, §60.42.
[39] Texas Administrative Code, Title 30, Section 1, §117.105, and Ibid, §112.8.
[40] Code of Federal Regulations, Title 40, Chapter 1, §63.602.
[41] New York Environmental Conservation Rules and Regulations, §216.3.
[42] Texas Administrative Code, Title 30, Section 1, §106.352.
[43] New York Environmental Conservation Rules and Regulations §223.3.

[44] Exceptions include Hochman and Zilberman (1978), who model standards as limits on emissions per unit output or per unit input. Harford and Karp (1983) compare the two policies and find that a standard per unit output is more efficient than a standard per unit input. Similarly, Thomas (1980) compares the welfare costs of different policies. Fullerton and Metcalf (2001) model a technology restriction as a limit per unit output. Fredriksson et al (2004) model environmental policy as a limit on the energy-capital ratio, citing the Corporate Average Fuel Economy Standards. None of these studies investigate distributional

mandates is in Helfand (1991). Her model contains a single consumption good produced using a "dirty" input that causes pollution and a "clean" one that abates pollution. The various mandates considered are: a limit on emissions, a limit on output, an upper limit on the dirty input, a lower limit on the clean input, and limits on the ratio of emissions to output or the ratio of emissions to either of the inputs. By normalizing all of these types of standards so that they result in the same reduction in emissions, she can compare their effects on output produced, inputs used, and firm profits. For example, she finds that the restriction on output most reduces input and output levels. The restriction on pollution itself yields the highest firm profits. In most cases, however, the signs of these changes depend on the form of the production function. Some counterintuitive results are reached as well. For instance, a standard per unit output may actually increase total emissions; the same result may occur from a standard limiting total output. More recently, Jou (2004) compares absolute emissions standards with emissions/output standards and finds that the former leads to less pollution.[45]

While the Helfand paper provides a number of valuable insights regarding the differences between types of mandates, it does not speak to the question of incidence.[46] In fact, the input supply curves are horizontal, so no policy can have incidence on the sources side, even in a partial equilibrium model. In contrast, our general equilibrium model allows for endogenous input prices as well as output prices. Furthermore, the two inputs in Helfand's model are a clean and dirty input. Even as these two input prices change, the implications are unclear for returns to labor and capital. Similarly, while Jou's model solves for the impact of policy on capital investment, the wage rate is set

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impacts. Burtraw et. al. (2001) and Fischer and Fox (2004) present computational models which compare policies with different allocation rules for emissions permits, and they present distributional effects.

45 Also, Goulder et al (1999) compare efficiency effects of environmental policies in the presence of distortionary taxes. McKitrick (2001) solves for the efficiency costs of ratio standards. Aidt and Dutta (2004) develop a political economy model of the choice of policy and find that the increasing use of incentives follows from increasingly high environmental goals. See also Keohane et al (1998) for a similar model of policy choice. Montero (2002) compares effects on R&D incentives, while Requate and Unold (2003) compare incentives to adopt abatement technology. Bovenberg et al (2005) look at how the efficiency costs of mandates and taxes are affected by a constraint to avoid adverse industry-distributional effects.

exogenously. Here, we model production as using capital, labor, and pollution. All three inputs have endogenous prices, so we can capture the differential effects of environmental standards on the relative returns to labor and capital. Which factors gain or lose can have a large effect on what policies are chosen (Keohane et al 1998).

## 2.2. Tradable Pollution Permits

Before turning to the main results of this paper, which concern the incidence of relative standards, we begin by introducing a simpler model of emissions permits. The distributional effects of a tradable permit policy depend on how those permits are allocated. The permits impose costs by forcing firms to reduce emissions or to buy permits. The mandated overall limit on pollution creates scarcity rents, however, and the distribution of those rents must be considered as part of the incidence.[47] If the permits are grandfathered to the firms, then their owners capture those scarcity rents by not having to pay for those emissions. If permits are auctioned, then the government captures those rents and can use the funds in various ways. In addition to evaluating changes in returns to capital and labor, our model solves for changes in permit-created scarcity rents. All three of these price changes contribute to the sources-side incidence of the policy.

Our model is similar to that in Fullerton and Heutel (2007), where we analyze only a tax on emissions. We start with an absolute quantity limit because it is most analogous to the tax on emissions: with many identical firms and no uncertainty, the model of firm decision making is the same whether the firm faces a tax or a permit price per unit of emissions. Like Harberger (1962), this model compares two equilibria rather than the transition period between them.[48]

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[46] Helfand and House (1995) empirically estimate the costs of different environmental policies for lettuce growers in California's Salinas Valley. They find that mandates reduce farm profits less than do taxes.

[47] In a partial equilibrium model, Parry (2004) estimates the distribution of scarcity rents created by emissions permits for carbon, $SO_x$ and $NO_x$.

[48] For a CGE model which analyzes transitions due to imperfect factor mobility, see Goulder and Summers (1989). Even if one is only interested in the equilibrium and not the transitions, it is possible that adding imperfect mobility or adjustment costs alters the equilibrium.

Our closed economy consists of two competitive sectors, one that produces a clean good ( $X$ ) and one that produces a dirty good ( $Y$ ). Output prices are $p_X$ and $p_Y$, respectively. The clean sector uses only capital and labor in production ( $K_X$ and $L_X$); the dirty sector uses capital, labor, and pollution ( $K_Y$, $L_Y$, and $Z$). As in the Harberger (1962) model, capital and labor are perfectly mobile and are available in fixed total supply. Totally differentiating the resource constraints gives:

$$\hat{K}_X \lambda_{KX} + \hat{K}_Y \lambda_{KY} = 0 \tag{1}$$

$$\hat{L}_X \lambda_{LX} + \hat{L}_Y \lambda_{LY} = 0 \tag{2}$$

where a hat over a variable represents a proportional change (e.g. $\hat{K}_X \equiv dK_X / K_X$ ). The ${}_{ij}$ parameter represents sector $j$'s share of input $i$ (e.g. $\lambda_{KX} \equiv K_X / \overline{K}$ , where $\overline{K}$ is the total capital available in the economy).

The clean sector's production decision can be characterized by ${}_X$, the elasticity of substitution in production between capital and labor:

$$\hat{K}_X - \hat{L}_X = \sigma_X (\hat{w} - \hat{r}) \tag{3}$$

where $w$ and $r$ are the returns to labor and capital, respectively. The choice of inputs in the dirty sector can be modeled using input demand equations for each of the three inputs (capital, labor, and pollution). While economy-wide pollution is set exogenously by the total number of permits, each individual firm chooses its own level of $Z$ based on the market permit price it faces, $p_Z$. We differentiate the three input demand equations and use the fact that only two of the three are independent to get:

$$\hat{K}_Y = a_{KK}\hat{r} + a_{KL}\hat{w} + a_{KZ}\hat{p}_Z + \hat{Y} \tag{4}$$

$$\hat{L}_Y = a_{LK}\hat{r} + a_{LL}\hat{w} + a_{LZ}\hat{p}_Z + \hat{Y} \tag{5}$$

where $a_{ij}$ is the elasticity of demand for factor $i$ with respect to the price of factor $j$. Allen (1938) shows that $a_{ij} = {}_{Yi}e_{ij}$, where ${}_{Yi}$ is the share of production for factor $i$ in sector $Y$ (e.g. $\theta_{YK} \equiv \dfrac{rK_Y}{p_Y Y}$), and $e_{ij}$ is the Allen elasticity of substitution between inputs

$i$ and $j$.[49] The assumptions of perfect competition and constant returns to scale production yield the following equations:

$$\hat{p}_X + \hat{X} = \theta_{XK}(\hat{r} + \hat{K}_X) + \theta_{XL}(\hat{w} + \hat{L}_X) \tag{6}$$

$$\hat{p}_Y + \hat{Y} = \theta_{YK}(\hat{r} + \hat{K}_Y) + \theta_{YL}(\hat{w} + \hat{L}_Y) + \theta_{YZ}(\hat{p}_Z + \hat{Z}) \tag{7}$$

$$\hat{X} = \theta_{XK}\hat{K}_X + \theta_{XL}\hat{L}_X \tag{8}$$

$$\hat{Y} = \theta_{YK}\hat{K}_Y + \theta_{YL}\hat{L}_Y + \theta_{YZ}\hat{Z} \,. \tag{9}$$

In these equations, we suppose an existing permit restriction, so that the initial price $p_Z$ is positive and pollution $Z$ is finite. We then suppose an exogenous decrease in the number of emissions permits, $\hat{Z} < 0$.

Finally, consumer preferences are modeled using $_u$, the elasticity of substitution in consumption between the clean and dirty goods:

$$\hat{X} - \hat{Y} = \sigma_u(\hat{p}_Y - \hat{p}_X) \tag{10}$$

The clean good is chosen as numeraire, so $\hat{p}_X$ is fixed at zero, and we have ten equations for the ten unknown changes: $\hat{K}_X, \hat{K}_Y, \hat{L}_X, \hat{L}_Y, \hat{w}, \hat{r}, \hat{X}, \hat{p}_Y, \hat{Y}, \hat{p}_Z$. Thus, the system can be solved by successive substitution. The steps are omitted but may be requested from the authors. While the model can be used to solve for all ten endogenous variables, we report here only the solutions for $\hat{r}$, $\hat{w}$, $\hat{p}_Z$, and $\hat{p}_Y$. The first three of these determine the sources-side incidence of the policy, and the last determines the uses-side incidence. Because $X$ is produced with no excess profit using only labor and capital, and its output price is fixed by assumption, $r$ and $w$ cannot both move in the same direction. If $\hat{r} = \hat{w} = 0$, the implication is not that factors bear no burdens. Rather, since $p_Y$ may rise, $\hat{r} = \hat{w} = 0$ means that labor and capital bear burdens in proportion to their shares of national income. Hence, a positive value for $\hat{r}$ just means that capital bears less of the burden than does labor.

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[49] See also Mieszkowski (1972) for an example of the same methodology. Note that the stability conditions for the input demand system are satisfied so long as the own price elasticities $e_{ii}$ are negative, which is assumed here.

The general solutions are presented in Table 2.1, but some are difficult to interpret. In the factor price equations, we can see effects first identified by Mieszkowski (1967). The first term in the curly brackets is his "output effect": assuming the denominator $D$ is positive, the policy $\hat{Z} < 0$ raises the cost of production and thus reduces output in a way that depends on consumer preferences $_u$. Then if $Y$ is capital intensive, ( $_K$ – $_L$)>0, the output effect reduces $r$ and raises $w$. The other terms represent a "substitution effect": they involve the Allen elasticities, $e_{KZ}$ and $e_{LZ}$, which determine whether labor or capital is a better substitute for pollution. However, the equations for $p_Z$ and $p_Y$ seem quite cumbersome. To make the interpretations clearer and to see the importance of various effects, we briefly consider the effect of factor prices ($r$ and $w$) in two special cases: equal factor intensities (to isolate the substitution effect), and no substitution in the dirty sector (to see the output effect).

**Table 2.1: Incidence of Absolute Quantity Restrictions**

$$\hat{r} = \frac{\theta_{YZ}\theta_{XL}}{D}\{\sigma_u(\gamma_K - \gamma_L) - e_{KZ}\gamma_K(1+\gamma_L) + e_{LZ}\gamma_L(1+\gamma_K)\}\hat{Z},$$

$$\hat{w} = \frac{\theta_{YZ}\theta_{XK}}{D}\{-\sigma_u(\gamma_K - \gamma_L) + e_{KZ}\gamma_K(1+\gamma_L) - e_{LZ}\gamma_L(1+\gamma_K)\}\hat{Z},$$

$$\hat{p}_Z = F^{-1}\{(\frac{1}{D})(G\gamma_L(1+\gamma_K) - F\gamma_K(1+\gamma_L))(\frac{\sigma_X}{A}(C+\beta_L) + \theta_{YL}\theta_{XK}(e_{KL} - e_{KK})) - \frac{\gamma_L(1+\gamma_K)}{A}\}\hat{Z}$$

$$\hat{p}_Y = \{[G\gamma_L(1+\gamma_K) - F\gamma_K(1+\gamma_L)][\frac{\theta_{YZ}}{D}(\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK}) + \frac{\sigma_X(C+\beta_L) + A\theta_{YL}\theta_{XK}(e_{KL} - e_{KK})}{AFD}] - \frac{\theta_{YZ}\gamma_L(1+\gamma_K)}{FA}\}\hat{Z}$$

where: $\gamma_L \equiv \dfrac{\lambda_{LY}}{\lambda_{LX}} = \dfrac{L_Y}{L_X} > 0$, $\quad \gamma_K \equiv \dfrac{\lambda_{KY}}{\lambda_{KX}} = \dfrac{K_Y}{K_X} > 0$, $\quad \beta_K \equiv \theta_{XK}\gamma_K + \theta_{YK} > 0$,

$$\beta_L \equiv \theta_{XL}\gamma_L + \theta_{YL} > 0, \quad A \equiv \gamma_L\beta_K + \gamma_K\beta_L > 0, \quad C \equiv \beta_K\theta_{YL} - \beta_L\theta_{YK},$$

$F \equiv \sigma_u(\dfrac{\gamma_L(1-\theta_{YK}) - \gamma_K\theta_{YL}}{A}) + e_{KZ}$, $\quad G \equiv \sigma_u(\dfrac{\gamma_K(1-\theta_{YL}) - \gamma_L\theta_{YK}}{A}) + e_{LZ}$, and

$$\begin{aligned}D \equiv\ & \sigma_u[\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK}][G(A-\gamma_L(1+\gamma_K)) - F(A-\gamma_K(1+\gamma_L))] \\ & + \sigma_X[G(C+\beta_L) + F(\beta_K - C)] + A\theta_{XL}\theta_{YK}[Fe_{KL} - Ge_{KK}] - A\theta_{YL}\theta_{XK}[Fe_{LL} - Ge_{KL}]\end{aligned}$$

### 2.2.1 Equal Factor Intensities

The assumption of equal factor intensities means that $_L$ and $_K$ are equal to each other. Let their common value be , and note that this condition implies that $L_Y/L_X = K_Y/K_X$. The output effect then disappears, and the substitution effect simplifies. For this permit policy, we then have:

$$\hat{r} = -\frac{\theta_{YZ}\theta_{XL}}{D}\gamma(1+\gamma)(e_{KZ} - e_{LZ})\hat{Z}$$

$$\hat{w} = \frac{\theta_{YZ}\theta_{XK}}{D}\gamma(1+\gamma)(e_{KZ} - e_{LZ})\hat{Z}$$

and the denominator $D$ in the general solution reduces to

$$\begin{aligned}D = \ & \sigma_X[\theta_{YZ}\sigma_u + (\theta_{XL}\gamma + \theta_{YL})e_{LZ} + (\theta_{XK}\gamma + \theta_{YK})e_{KZ}] \\ & + A[\theta_{XL}\theta_{YK}(Fe_{KL} - Ge_{KK}) - \theta_{YL}\theta_{XK}(Fe_{LL} - Ge_{KL})]\end{aligned}$$

Under the assumption that all three Allen cross-price elasticities $e_{ij}$ are positive, the denominator $D$ must be positive.[50] In this case, we reach a definitive conclusion about the effect of the regulation on $r$ and $w$. The signs of these price changes depend on the sign of $(e_{KZ} - e_{LZ})$. When emissions must be reduced, the dirty sector wants to substitute into both labor and capital, but if labor is a better substitute for pollution ($e_{LZ} > e_{KZ}$), then labor is hurt relatively less by the policy (i.e. $\hat{r} < 0$ and $\hat{w} > 0$).

Surprisingly, this simple intuition cannot be applied to the effect of the policy on the permit price.[51] The decrease in permits allocated creates a "direct effect" that raises the permit price: it reflects a downward-sloping demand curve for emissions permits, so

[50] In fact, this assumption is sufficient but not necessary. A less restrictive assumption also suffices, namely that the cross-price elasticity between capital and labor is not too negative. Here, we do not consider the implications of this condition failing. For a discussion of that topic, see Fullerton and Heutel (2007).

[51] The expression simplifies to

$$\hat{p}_Z = \frac{1}{F}\{-\frac{\gamma(1+\gamma)}{D}(e_{KZ} - e_{LZ})[\frac{\sigma_X\beta_L}{A} + \theta_{YL}\theta_{XK}(e_{KL} - e_{KK})] - \frac{1+\gamma}{\theta_{YL} + \theta_{YK} + \gamma}\}\hat{Z}$$

the leftward shift of the vertical supply curve tends to raise the equilibrium permit price. However, an "indirect effect," related to factor substitutability, can work in the opposite direction, and may actually *decrease* the permit price. The conditions under which this counterintuitive effect occurs are quite cumbersome and difficult to interpret, and hence they are not presented here. Yet the effect is analogous to the earlier finding that an increase in the pollution tax can lead to an *increase* in emissions.[52]

Yet, unlike the incidence on labor and capital owners, the incidence on permit holders is not determined solely by the change in their factor price. Labor and capital are in fixed total supply and earn net returns determined by $w$ and $r$, but the supply of permits has just been restricted by the policy ($\hat{Z} < 0$). The total return to permit holders is $p_Z \cdot Z$, and the proportional change in this product is $\hat{p}_Z + \hat{Z}$. Even if the policy raises the price $p_Z$, then permit holders are still not necessarily better off.

Furthermore, even the uses-side incidence result ($\hat{p}_Y$) is ambiguous.[53] A direct effect works to increase the price of the dirty good, but an indirect effect may counter that. It allows for the possibility of another counter-intuitive result: reducing the number of emissions permits may hurt consumers of the clean good more than consumers of the dirty good.

### 2.2.2 No Substitution in Dirty Sector

To see the impact of factor intensities on the incidence of this policy, we now let the factor intensities of the two sectors differ but assume away any ability of the dirty sector to substitute among its inputs. That is, we assume $e_{ij} = 0$ for all $i, j$. While this is clearly a restrictive assumption, it allows us to isolate the impact of the factor intensities.

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[52] See DeMooij and Bovenberg (1998) or Fullerton and Heutel (2007). This example is comparable to the "Edgeworth Taxation Paradox" as studied in Hotelling (1932), where the imposition of a tax on a good can decrease its net-of-tax price. Though Hotelling's model is not perfectly analogous to the one here, his inequalities (25) and (26) present conditions when the paradox holds; they similarly involve cross-price demand elasticities.

[53] That expression simplifies to

$$\hat{p}_Y = \{-\gamma(1+\gamma)[e_{KZ} - e_{LZ}][\frac{\sigma_X \beta_L - A\theta_{YL}\theta_{XK}(e_{KL} - e_{KK})}{AFD}] - \frac{\theta_{YZ}\gamma(1+\gamma)}{FA}\}\hat{Z}$$

Under this assumption the denominator $D$ in Table 2.1 simplifies to $\;_{YZ}\;_{X}\;_{u}$, and the substitution effects in $\hat{r}$ and $\hat{w}$ disappear. The changes in factor prices become:

$$\hat{r} = \frac{\theta_{XL}}{\sigma_X}(\gamma_K - \gamma_L)\hat{Z}$$

$$\hat{w} = -\frac{\theta_{XK}}{\sigma_X}(\gamma_K - \gamma_L)\hat{Z}$$

In this case, the sources side incidence includes only an output effect, determined by the sign of $\;_K - \;_L$. This expression is positive whenever the dirty sector is capital-intensive. Suppose this is the case. Since $\hat{Z} < 0$, the rental rate falls and the wage rises relative to the numeraire; capital bears a disproportionately high burden of the policy. For firms unable to substitute among inputs, a reduction in pollution permits forces the dirty industry to use less labor and capital in equal proportions. If the dirty industry is capital-intensive, then the decreased demand for capital exceeds the decreased demand for labor, and the rental rate falls. The magnitude of this effect is mediated by $\;_X$, the elasticity of substitution in production of the clean good. If the clean industry can easily substitute between capital and labor, then these effects on input prices become smaller, since the clean sector can more easily accommodate the additional labor or capital.

Again, as before, the effects on the permit price and the output price are not as intuitive.[54] Both contain a direct effect that moves the price in the expected direction (increasing) and an indirect effect that could move the price in the counterintuitive direction. In other words, the effect of factor intensities on relative input prices follows intuition, but effects on permit and output prices are more complicated. The ambiguities remain even though the assumption in this case eliminates the factor substitution effect.

### 2.3. Command and Control Restrictions on Firm-Specific Pollution Quantities

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[54] These expressions are $\hat{p}_Z = -\frac{1}{\sigma_u[\gamma_L(\theta_{YK}-1)+\gamma_K\theta_{YL}]}\{\frac{(\gamma_K-\gamma_L)}{\theta_{YZ}}(C+\beta_L)-\gamma_L(1+\gamma_K)\}\hat{Z}$ and $\hat{p}_Y = \{(\gamma_K-\gamma_L)[-\frac{1}{\sigma_X}(\theta_{YK}\theta_{XL}-\theta_{YL}\theta_{XK})-\frac{C+\beta_L}{AF\theta_{YZ}}]-\frac{\theta_{YZ}\gamma_L(1+\gamma_K)}{FA}\}\hat{Z}$.

We started with tradable pollution permits above, because the permit market is easy to comprehend with a vertical supply, a downward-sloping demand, and many identical firms that each can buy as many permits as desired at the equilibrium market price $p_Z$. Then all firms in the dirty industry have symmetric demands for the three inputs $(K, L, Z)$ based on the three input prices $(r, w, p_Z)$.

We next consider briefly the case where *each* firm faces a restriction on its use of $Z$. Pollution has no market clearing price $p_Z$, but each firm with a restriction on $Z$ can be said to face a shadow price $p_Z$. Each firm gets an allocation of permits that are not tradable. In our model with many identical firms, however, the firms cannot gain from trade. With constant returns to scale, each firm's labor and capital can adjust to its allocation of nontradable permits in a way that is equivalent to the transfer of permits to some other firm using that same labor and capital. In other words, firm-specific restrictions on pollution levels in this model yield the same results as we just derived for tradable permits. Equations above can be used for effects on total dirty-industry use of labor and capital and for consequent economy-wide returns to labor and capital.

### 2.4. "Performance Standard": Emissions per unit Output

An alternative form of environmental policy is to limit the ratio of emissions to output, a policy we call a "performance standard". With heterogeneous firm sizes, at least some consideration of this ratio seems necessary for a plausible policy. A large producer cannot reasonably be expected to achieve the same limit on emissions as a small firm. Considerations like these are also taken into account in other policies, such as a fixed number of tradable permits that are initially allocated according to market share. If firm-specific emission limits are tied directly to the firm's output level, then the policy may have no absolute limit on total emissions. Instead, total emissions vary with total output in a way that affects incentives and prices.

We consider the same production functions as in the previous section. Total capital and labor are in fixed supply, as in equations (1) and (2). Likewise, production in the clean sector is unchanged, with equations (3), (6), and (8). Consumer preferences in equation (10) remain unchanged. The only change is to incentives facing firms in the dirty sector. The maximization problem for these firms is:

$$\max_{K_Y, L_Y, Z} \quad p_Y Y(K_Y, L_Y, Z) - rK_Y - wL_Y$$

subject to the constraint $Z/Y \leq \delta$. The firms pay no explicit price for the input $Z$. Instead, their use of that input is limited by their output. The constraint must bind, since the production function is monotone increasing in all inputs.[55] Solving the firms' first order conditions and rearranging terms yields $r = \dfrac{p_Y Y_K}{1 - \delta Y_Z}$ and $w = \dfrac{p_Y Y_L}{1 - \delta Y_Z}$, where subscripts on $Y$ denote marginal products. The firm does not set the marginal value of an input equal to the input price, as it would without the performance standard, because of the denominator in these two equations. This denominator is less than one, so the marginal value of the factor is set lower than its input price. In other words, the firm wants to proceed further down its factor demand curves, using more labor and capital in order to increase output and qualify for an increase in valuable emission rights.

Totally differentiating the production function and substituting in these equations yields the equation analogous to (9) in the previous model:

$$\hat{Y} = \theta_{YK}(1 - \nu)\hat{K}_Y + \theta_{YL}(1 - \nu)\hat{L}_Y + \nu\hat{Z}\,, \tag{9'}$$

where $\nu \equiv \delta Y_Z = Y_Z Z/Y$. In the prior model with (9), an increase in a factor would raise output in proportion to its factor share. Now, since the marginal product of each factor is reduced by (1 – ), its marginal contribution to output is reduced by (1 – ). An increase in emissions $Z$ raises output in proportion to = $Y_Z$, to reflect its marginal product $Y_Z$ and its factor share = $Z/Y$. Emission rights are valuable, of course, but firms do not pay for them through an explicit price. Instead, they pay for emission rights by paying factors more than their marginal products.

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[55] Suppose that the constraint does not bind at the firm's optimum point of production. Firms could then increase use of $Z$ without changing their use of $K$ or $L$. Then output and revenue would increase, since the marginal product of $Z$ is positive, with no change in costs. Therefore, the initial point was *not* an optimum, a contradiction.

The assumptions of perfect competition and free entry/exit lead to a zero profit condition in the previous model. This condition remains under the policy specified here, though it takes a different form. Since costs no longer include the price of emission permits, the final term in equation (7) is dropped. The zero profit condition thus implies

$$\hat{p}_Y + \hat{Y} = \theta_{YK}(\hat{r} + \hat{K}_Y) + \theta_{YL}(\hat{w} + \hat{L}_Y)\,. \tag{7'}$$

The constraint may impose a "shadow price" on the factor $Z$, but since no explicit price is paid for that input, it is not included in the profits equation.[56]

Finally, we must replace equations (4) and (5) with their counterparts under the new policy. Input demand equations can no longer be functions of output and three explicit input prices ($r$, $w$, $p_Z$). Instead, we write input demand equations as functions of $r$, $w$, , and $Y$. Then totally differentiate these equations to get:

$$\hat{K}_Y = b_{KK}\hat{r} + b_{KL}\hat{w} + b_{KZ}\hat{\delta} + \hat{Y}$$

$$\hat{L}_Y = b_{LK}\hat{r} + b_{LL}\hat{w} + b_{LZ}\hat{\delta} + \hat{Y}$$

$$\hat{Z} = b_{ZK}\hat{r} + b_{ZL}\hat{w} + b_{ZZ}\hat{\delta} + \hat{Y}\,.$$

Notice that the $b_{ij}$ variables appear in a form similar to the $a_{ij}$ variables in equations (4) and (5). They both represent input demand elasticities. For example, either $a_{KL}$ or $b_{KL}$ is the percent change in capital for a one percent change in the wage. However, $a_{KL}$ is that response in the first model holding $p_Z$ and $Y$ constant (so $Z$ can change), while $b_{KL}$ is that response in the model holding and $Y$ constant (so $Z =$ $Y$ cannot change).[57]

The third equation giving the input demand for $Z$ can be simplified greatly. We know that the constraint binds, so $Z =$ $Y$. Then total differentiation yields:

$$\hat{Z} = \hat{\delta} + \hat{Y}\,, \tag{5'}$$

which implies that $b_{ZK} = b_{ZL} = 0$, and $b_{ZZ} = 1$. Since only two of the three equations are independent, we subtract the second equation from the first and get

$$\hat{K}_Y - \hat{L}_Y = b_r\hat{r} + b_w\hat{w} + b_\delta\hat{\delta}\,, \tag{4'}$$

---

[56] This alters the dynamic of firm entry and exit, but since our concern is general equilibrium effects and not the transition periods leading up to them, it does not affect our results.

[57] The $b_{ij}$ elasticities (and the $c_{ij}$ elasticities from the following section) are similar in concept to the direct and indirect substitution effects of Ogaki (1990).

where $b_r = b_{KK} - b_{LK}$, $b_w = b_{KL} - b_{LL}$, and $b \ = b_{KZ} - b_{LZ}$. In Appendix A2, we calculate values of the $b_{ij}$ elasticities. Although differences between the $a_{ij}$ and $b_{ij}$ parameters were just described, it helps to think of them analogously. Appendix A2 shows that $b_{KK}$ and $b_{LL}$ are negative, since increasing the price of a factor decreases its demand, even with the constraint on $\ =Z/Y$. It also shows that the cross-price values $b_{ij}$ are positive ($i,j = K,L$). This is true whether or not capital and labor are substitutes as defined by the sign of the Allen cross-price elasticity. That is, a higher price of labor means more capital demand. Why is complementarity ruled out in this case? The Allen elasticities are defined for the input demand functions where all three inputs are allowed to vary. Raising the price of labor $w$ may then decrease the demand for capital, if the two inputs are complements, but the firm would be forced to increase its other input, pollution. Here, however, the third input demand equation ($\hat{Z} = \hat{\delta} + \hat{Y}$) indicates that a change in $w$, with no change in   or $Y$, cannot change $Z$. Only labor and capital can vary, so they must be substitutes.

Thus, in (4'), a higher wage increases the capital/labor ratio ($b_w > 0$), and higher price of capital reduces it ($b_r < 0$). In fact, Appendix A2 shows that $b_r = -b_w$. Finally, we show in Appendix A2 that $b \ = b_{KZ} - b_{LZ}$ has the opposite sign of $e_{KZ} - e_{LZ}$. A tighter regulation means that   is decreased, and less pollution is allowed per unit output. If capital is a better substitute for pollution than is labor, that is, if $e_{KZ} > e_{LZ}$, then more capital must be used relative to labor ($b_{KZ} < b_{LZ}$, and hence $b$ is negative). If $b$ is positive, then labor is a better substitute than is capital: a tightening of environmental policy means lower   and lower $K/L$ ratio.

For this model we now have ten equations: (1), (2), (3), (4'), (5'), (6), (7'), (8), (9'), and (10). As before, we set $\hat{p}_X = 0$ and solve for the changes in returns to capital and labor attributable to a small change in the policy variable ( ). The solutions are presented in Table 2.2. Compared to the general solutions in Table 2.1, these equations are not as difficult to interpret. Firstly, the denominator $D$ is positive-definite. Secondly, the expressions for $\hat{r}$ and $\hat{w}$ can be decomposed into three terms, each corresponding to a single effect. The second term is the "output effect," as before, and the last term is the "substitution effect". Here, however, the first term is a new effect we call an "output-subsidy effect": since the policy mandates a lower *ratio* of pollution to output, it can be satisfied partially by increasing output (which helps the factor used intensively). We again analyze these effects by focusing on two special cases.

**Table 2.2: Performance Standard (Restriction on Z/Y)**

$$\hat{r} = [-\frac{\theta_{XL}\nu}{D}(\gamma_K - \gamma_L) + \frac{\theta_{XL}\nu\sigma_u}{D}(\gamma_K - \gamma_L) + \frac{\theta_{XL}\eta}{D}b_\delta]\hat{\delta}$$

$$\hat{w} = [\frac{\theta_{XK}\nu}{D}(\gamma_K - \gamma_L) - \frac{\theta_{XK}\nu\sigma_u}{D}(\gamma_K - \gamma_L) - \frac{\theta_{XK}\eta}{D}b_\delta]\hat{\delta}$$

$$\hat{p}_Y = \{\frac{1}{D}(\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK})(-\nu(1-\sigma_u)(\gamma_K - \gamma_L) + \eta b_\delta) - \frac{\nu}{1-\nu}\}\hat{\delta}$$

where $\eta \equiv (\theta_{YK}\gamma_L + \theta_{YL}\gamma_K + 1)(1-\nu) > 0$ and

$$D \equiv (1-\nu)\sigma_u(\theta_{XL}\theta_{YK} - \theta_{YL}\theta_{XK})(\gamma_K - \gamma_L) + \eta[b_w + \sigma_X(\theta_{XL}\gamma_L + \theta_{XK}\gamma_K)] > 0$$

### 2.4.1 Equal Factor Intensities

Since the output effect and output-subsidy effect operate through differential factor intensities, the assumption ${}_K = {}_L =$ makes them both disappear. Then only the third term for the substitution effect remains in $\hat{r}$ and $\hat{w}$. The solutions reduce to:

$$\hat{r} = \frac{\theta_{XL}\gamma b_\delta}{\sigma_X + \gamma b_w}\hat{\delta}$$

$$\hat{w} = \frac{-\theta_{XK}\gamma b_\delta}{\sigma_X + \gamma b_w}\hat{\delta}$$

$$\hat{p}_Y = \frac{-\nu}{1-\nu}\hat{\delta}.$$

In this case, the factor that is a relative substitute for pollution is burdened less by a strengthening of environmental policy ( $\hat{\delta} < 0$ ). If labor is the better substitute for pollution ($b > 0$), the coefficient in front of $\hat{\delta}$ in the first expression is positive. Then the return to capital falls, while the return to labor rises. In fact, note that this simple intuition could fail with the emissions permit market. Here, this intuition cannot fail since the sign of the denominator cannot switch.

This case also provides unambiguous results for incidence on the uses side of income. Only the last term remains from the long expression for $\hat{p}_Y$ in Table 2.2, and it is negative. A tightening of environmental policy increases the price of the dirty good relative to the price of the clean good, hurting consumers of the dirty good.

### 2.4.2 No Substitution Effect in Dirty Sector

As we did with the previous policy, we can isolate the effect of factor intensities by assuming away differential substitution in the dirty sector. In the previous case we set all $a_{ij}$ to zero, but here we set only $b$ to zero.[58] Under the policy in question, then, any change in the policy parameter has no effect on the relative input demands for capital and labor. Hence, the substitution effect is eliminated. Under these assumptions, the general solutions reduce to:

$$\hat{r} = -\frac{1}{D}\theta_{XL}\nu(1-\sigma_u)(\gamma_K - \gamma_L)\hat{\delta}$$

$$\hat{w} = \frac{1}{D}\theta_{XK}\nu(1-\sigma_u)(\gamma_K - \gamma_L)\hat{\delta}$$

$$\hat{p}_Y = [-(\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK})\nu(1-\sigma_u)(\gamma_K - \gamma_L)\frac{1}{D} - \frac{\nu}{1-\nu}]\hat{\delta},$$

where $D \equiv (1-\nu)\sigma_u(\theta_{XL}\theta_{YK} - \theta_{YL}\theta_{XK})(\gamma_K - \gamma_K) + \eta\sigma_X(\theta_{XL}\gamma_L + \theta_{XK}\gamma_K) > 0$.

---

[58] We cannot set all $b_{ij}$ elasticities to zero, since Appendix A2 shows that some of them are of definite sign.

In the first two expressions, we combine the "output effect" and the "output-subsidy effect" from the general solutions in Table 2.2. Suppose that the dirty sector is capital intensive, so that $( {}_K - {}_L) > 0$. Then, capital is hurt more than labor from a tightening of policy only if ${}_u$, the elasticity of substitution in consumption between $X$ and $Y$, is greater than one. Tightening the policy imposes a burden on the dirty sector only, hurting capital when $Y$ is capital-intensive. This is the "output effect." However, the tighter policy can be accommodated by producing more $Y$, since that drives down the $Z/Y$ ratio. This is the "output-subsidy effect," helping capital. The usual output effect dominates only when ${}_u > 1$. If consumers are *not* highly responsive to relative output prices, then the output-subsidy effect dominates, and tighter environmental policy places *less* burden on the factor that is used intensively in the dirty sector.[59]

The three effects of a tighter performance standard are summarized in Table 2.3. Each entry shows the sign of that column's effect on that row's price. For example, the box in the first row and first column contains $( {}_L - {}_K)$. If that term is positive ($Y$ is labor intensive), then a tighter performance standard increases the rental rate. The table shows that the output effect and the output-subsidy effect always work in opposite directions, and always through the relative factor intensity of the two sectors. The substitution effect depends on $b$, which is equal in sign to $e_{KZ} - e_{LZ}$.

**Table 2.3: Summary of Effects from a Tighter Performance Standard**

| | Output Effect | Output-Subsidy Effect | Substitution Effect |
|---|---|---|---|
| $\hat{r}$ | $( {}_L - {}_K)$ | $( {}_K - {}_L)$ | $b$ |
| $\hat{w}$ | $( {}_K - {}_L)$ | $( {}_L - {}_K)$ | $-b$ |

[59] It is possible to create the same effects as a restriction on pollution per unit output with a combination of a tax on pollution and a subsidy on output. In fact, the performance standard modeled in this section can be described as an implicit tax and subsidy combination. One can calculate the values of the tax and subsidy that will induce the same effects as a particular change in the performance standard. However, as argued in Section 1, real environmental mandates often take the form of performance standards, and rarely take the form of taxes and subsidies. We choose to maintain the performance standard as modeled to more closely assess the impact of real environmental policies.

**2.5. "Technology Mandate": Emissions per unit Input**

Whereas the previous section examines a limit on emissions per unit output, we now examine a regulation that limits emissions per unit of an input. Such limits are common, as described in our first section above. We have only two clean inputs in our model, so we capture the nature of a limit on emissions per unit input by modeling a limit on emissions per unit of capital. We refer to this policy as a technology mandate, since forcing the adoption of a particular technology in production may effectively fix the emissions/capital ratio. Capital and labor are each in fixed supply and mobile between sectors, so they are perfectly symmetric in this model. Thus, the results for a limit per unit labor can be obtained directly from results below by interchanging every $K$ and $L$ (as well as every $w$ and $r$).

As with the other two policies considered earlier, the equations that describe the behavior of consumers and of producers of the clean good do not change here. Equations (1), (2), (3), (6), (8), and (10) fall into this category and are applicable to this section. The only aspect of the model that requires revision is the behavior of producers of the dirty good. Consider their maximization problem. As in the previous policy considered, firms pay no explicit price for the pollution input. Instead, they face an exogenous ceiling on their ratio of emissions to capital. Formally, this problem is

$$\max_{K_Y, L_Y, Z} \quad p_Y Y(K_Y, L_Y, Z) - rK_Y - wL_Y$$

subject to the constraint $Z/K_Y$ • . A tightening of environmental policy is defined as a decrease in . It is clear that the policy constraint binds: since firms pay no price per unit of pollution, and this input is productive, they will employ as much of it as possible, an amount $Z = \ K_Y$. Thus, we use below the fact that $\partial Z/\partial K_Y = \ $. The first order conditions for the maximization problem are

$$r = p_Y(Y_K + \ Y_Z)$$

$$w = p_Y Y_L.$$

The second of these equations is identical to the first order condition in the original problem where firms face a price for all three inputs and no other constraint: the marginal value of labor is equal to the wage. The first equation differs from the standard condition. For the choice of capital input demanded, the marginal value of capital is *lower* than the rental rate (since $Y_Z$ is positive). The intuition here is that each unit of capital employed gives value to the firm in two different ways. First, it increases their output directly (since $Y_K > 0$). Second, it allows more pollution, which also increases output. The second term represents this effect, since $Y_Z$ is the marginal product of pollution and $= \partial Z/\partial K_Y$ is the pollution increase made possible by the increased capital. The value of investing in a marginal unit of capital is composed of these two terms and at the optimum is set equal to the cost of that investment, the rental rate $r$.

Totally differentiate the production function and substitute in these first order conditions. After dividing through by $Y$, we have:

$$\hat{Y} = (\theta_{YK} - \nu)\hat{K}_Y + \theta_{YL}\hat{L}_Y + \nu\hat{Z} \tag{9''}$$

The constant is still equal to $Y_Z Z/Y$, as in the previous section. Also, as before, an increase in any one input does not generally increase output by a proportion equal to its factor share. This condition does hold for labor in (9''), since that input choice is not distorted by the technology mandate. It cannot hold for pollution, however, since no share is "paid" to that input. Also, the constraint distorts the choice of capital. Yet, from (9''), we do see that a one percent increase in all three inputs yields a one percent increase in output, from the assumption of constant returns to scale. The zero profit condition still holds as well, even though firms do not pay for pollution, because entry and exit are still allowed. Thus equation (7') from the prior model also applies to this one.

Finally, the dirty sector's chosen amount of each input ($K_Y$, $L_Y$, and $Z$) depends on input prices, the policy parameter, and output ($r$, $w$, , and $Y$). We totally differentiate these input demand equations to get:

$$\hat{K}_Y = c_{KK}\hat{r} + c_{KL}\hat{w} + c_{KZ}\hat{\zeta} + \hat{Y}$$

$$\hat{L}_Y = c_{LK}\hat{r} + c_{LL}\hat{w} + c_{LZ}\hat{\zeta} + \hat{Y}$$

$$\hat{Z} = c_{ZK}\hat{r} + c_{ZL}\hat{w} + c_{ZZ}\hat{\zeta} + \hat{Y}\,.$$

The elasticity of demand for input $i$ with respect to price $j$ is defined here as $c_{ij}$ (but this response depends on the nature of the constraint, so the $c_{ij}$ elasticities are not the same as the $a_{ij}$ or $b_{ij}$ elasticities). Only two of these equations are independent of each other, so we subtract each of the bottom two equations from the top one to get two equations to use in our solution. The first of these equations is

$$\hat{K}_Y - \hat{L}_Y = c_r \hat{r} + c_w \hat{w} + c_\zeta \hat{\zeta} \,, \tag{4''}$$

where $c_r \equiv c_{KK} - c_{LK}$, $c_w \equiv c_{KL} - c_{LL}$, and $c \equiv c_{KZ} - c_{LZ}$. The second resulting equation can be simplified using the policy constraint $Z/K_Y =$ , since total differentiation gives:

$$\hat{K}_Y - \hat{Z} = -\hat{\zeta} \,. \tag{5''}$$

Substituting this into the equations above implies that $c_{KK} - c_{ZK} = 0$, $c_{KL} - c_{ZL} = 0$, and $c_{KZ} - c_{ZZ} = -1$. These relationships are verified in Appendix A3.

Also in that Appendix, we evaluate the elasticities of input demand. An important condition for their signs relates to the relative complementarity of capital and pollution. Let Condition 2 be defined as: $e_{KZ} > (e_{KK} + e_{ZZ})/2$. The right hand side of this inequality must be negative since all own-price elasticities are negative. This condition always holds, then, whenever capital and pollution are substitutes ($e_{KZ} > 0$). It also holds when capital and pollution are not "too" complementary. Appendix A3 shows that Condition 2 implies $c_r < 0$ and $c_w > 0$. That is, an increase in the capital rental rate must reduce the ratio $K_Y/L_Y$ demanded, and an increase in the wage rate must increase that ratio. The ratio of $Z$ to $K_Y$ is fixed, and so producers really have only two inputs between which they can substitute; once they choose $K_Y$ and $L_Y$, then $Z$ is given by the constraint. With only two inputs $K_Y$ and $L_Y$, they must be substitutes.

Now consider the case when Condition 2 fails (so that $c_r > 0$ and $c_w < 0$). Then an increase in $r$ *raises* the desired $K_Y/L_Y$ ratio (and an increase in $w$ raises relative labor demand). This result is highly counter-intuitive, but it can be explained by noting that capital and pollution are highly complementary in this case [$e_{KZ} < (e_{KK} + e_{ZZ})/2 < 0$]. Then a higher $r$ means that firms want less $K$ and less $Z$. Wanting less $Z$ reduces the pressure of the constraint ($Z/K_Y$ • ), which reduces the shadow price on $Z$ (i.e., the right to emit is not so valuable). The reduced shadow price on $Z$ by itself would mean more demand for $Z$ and more $K_Y$, since they are complements. If they are *sufficiently* complementary, then the result is a net increase in capital relative to labor.

**Table 2.4: Technology Mandate (Restriction on Z/K)**

$$\hat{r} = \frac{\theta_{XL}}{D}[-(1-\sigma_u)\nu(\gamma_K - \gamma_L) + [(\gamma_L(1+\gamma_K) + \theta_{YL}(\gamma_K - \gamma_L)]c_\zeta]\hat{\zeta}$$

$$\hat{w} = \frac{\theta_{XK}}{D}[(1-\sigma_u)\nu(\gamma_K - \gamma_L) - [(\gamma_L(1+\gamma_K) + \theta_{YL}(\gamma_K - \gamma_L)]c_\zeta]\hat{\zeta}$$

$$\hat{p}_Y = \{\frac{(\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK})}{D}[(1-\sigma_u)\nu(\gamma_L - \gamma_K) + [(\gamma_L(1+\gamma_K) + \theta_{YL}(\gamma_K - \gamma_L)]c_\zeta] - \nu\}\hat{\zeta}$$

$$\text{where} \quad \begin{aligned} D \equiv\ & \sigma_X(\theta_{XK}\gamma_K + \theta_{XL}\gamma_L + 1) + \sigma_u(\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK})(\gamma_K - \gamma_L) \\ & + (\theta_{XL}c_r - \theta_{XK}c_w)(\gamma_L(-1-\gamma_K) + \theta_{YL}(\gamma_L - \gamma_K)) \end{aligned}$$

The system of equations containing (1), (2), (3), (4"), (5"), (6), (7'), (8), (9"), and (10) are ten equations in ten unknowns, once we set $\hat{p}_X = 0$. In Table 2.4, these equations are solved for the proportional change in each price as a function of an exogenous change in . As in the previous policy, the expressions for $\hat{r}$ and $\hat{w}$ contain terms involving factor intensities and substitution elasticities (in this case $c$). The first term in these expressions, (1 – $_u$) ( $_K$ – $_L$), is similar to the output effects from section 2.4. The coefficient in front of $c$ is strictly positive, so the substitution effect depends on the sign of $c$. These effects are discussed in two special cases. When Condition 2 holds, the denominator $D$ must be positive..

### 2.5.1 Equal Factor Intensities

As before, the assumption $_K$ = $_L$ = makes the output effect disappear. Then only the substitution effect remains in $\hat{r}$ and $\hat{w}$. The solutions simplify to:

$$\hat{r} = \frac{\theta_{XL}\gamma c_\zeta}{\sigma_X + \gamma(c_w\theta_{XK} - c_r\theta_{XL})}\hat{\zeta}$$

$$\hat{w} = \frac{-\theta_{XK}\gamma c_\zeta}{\sigma_X + \gamma(c_w\theta_{XK} - c_r\theta_{XL})}\hat{\zeta}$$

$$\hat{p}_Y = -\nu\hat{\zeta}\ .$$

These equations are strikingly similar to their counterparts for the previous policy (but the $c_{ij}$ elasticities are not the same as the $b_{ij}$ elasticities). Suppose that Condition 2 holds, so that $c_r < 0$ and $c_w > 0$ (a higher rental rate decreases the $K/L$ ratio employed by the dirty sector, and a higher $w$ increases it). Then the denominator is positive in both expressions. The effect on factor prices then depends completely on the sign of $c$. A tighter environmental policy ($\hat{\zeta} < 0$) increases the return to capital relative to the wage if and only if $c < 0$ (which means $c_{KZ} < c_{LZ}$, so lower raises the desired $K/L$ ratio). Without differences in factor intensities, the policy change induces producers in the dirty sector to demand relatively more capital than labor, which raises the equilibrium $r$ relative to $w$. While this intuition is simple enough, the conditions for the sign of $c$ are not. Appendix A3 shows that $c$ can be written as:

$$c_{\zeta} = \frac{-M}{D'} + \frac{e_{LZ} - e_{KZ} + e_{KK} - e_{KL}}{-e_{KK} - e_{ZZ} + 2e_{KZ}},$$

where $M$ is positive always, and $D'$ is negative whenever Condition 2 holds. Supposing that Condition 2 holds, the denominator of the second fraction is positive. We identify two offsetting effects. First, the "capital-subsidy effect" is that firms can help satisfy the newly reduced $= Z/K_Y$ by raising $K_Y$ (making $c$ more likely negative). This effect is captured in the final three terms in the numerator $(-e_{KZ} + e_{KK} - e_{KL})$, which are negative when the cross-price elasticities are positive. Second, the first fraction $(-M/D')$ and $e_{LZ}$ in the second fraction are positive and represent a "substitution effect": to reduce $Z$, producers can raise $L_Y$ (making $c$ more likely positive). This substitution effect between $L$ and $Z$ is larger as the elasticity of substitution between these inputs, $e_{LZ}$, is larger. Which effect dominates depends in a complex way on the magnitudes of the Allen elasticities and the constants $M$ and $D'$.

On the uses side, incidence is unambiguous. A tighter environmental policy must increase the price of the dirty good relative to the price of the clean good – due to the direct effect of the policy on the cost of production in the $Y$ sector only.

### 2.5.2 No Substitution Effect in Dirty Sector

Here we assume that $c_r = c_w = c \ = 0$, or that no change in any input price or mandate has any effect on the ratio of $K/L$ demanded by the dirty sector. This is not quite as strong as saying that the dirty sector cannot substitute at all, since we do not assume that all of the $c_{ij}$ elasticities are zero.[60] Instead, our assumption simply eliminates the effects of substitution between labor and capital, and it thus allows us to consider only the effect of relative factor intensities. The solutions in this case reduce to:

$$\hat{r} = -\frac{\theta_{XL}}{D}(1-\sigma_u)\nu(\gamma_K - \gamma_L)\hat{\zeta}$$

$$\hat{w} = \frac{\theta_{XK}}{D}(1-\sigma_u)\nu(\gamma_K - \gamma_L)\hat{\zeta}$$

$$\hat{p}_Y = \{-\frac{\theta_{YK}\theta_{XL} - \theta_{YL}\theta_{XK}}{D}(1-\sigma_u)\nu(\gamma_K - \gamma_L) - \nu\}\hat{\zeta}\ ,$$

where the denominator $D = {}_{x}(\ {}_{XK}\ {}_{K} + \ {}_{XL}\ {}_{L} + 1) + \ {}_{u}(\ {}_{YK}\ {}_{XL} - \ {}_{YL}\ {}_{XK})(\ {}_{K} - \ {}_{L}) > 0$.

Just as in Section 2.4.2, then, the effect on relative factor prices depends on whether the elasticity of substitution in consumption, ${}_{u}$, is greater than one or less than one. Somewhat surprisingly, when the dirty sector is capital intensive, a tighter environmental policy can *raise* $r$ (whenever ${}_{u}$<1). For intuition, consider two effects of the reduction in $\ = Z/K_Y$. The "capital-subsidy effect" is that the tighter mandate can be met partially by using more $K_Y$. Since we have assumed in this section that the policy change has no effect on the ratio of $K/L$ demanded, this capital-subsidy effect also increases labor demand. If $Y$ is capital intensive, then this increases the ratio $r/w$. Second, the usual "output effect" is that the tighter mandate applies only to production of $Y$, which tends to raise the equilibrium price of $Y$ and reduce demand for $Y$ (and the use of both inputs $K_Y$ and $L_Y$). Under the continuing assumption that the dirty sector is capital intensive, this output effect reduces overall demand for capital and thus reduces $r/w$. These effects work in opposite directions, and they exactly offset when ${}_{u}$ = 1. In our simple model, ${}_{u}$<1 means that the output effect is dominated, and thus $r/w$ rises.

[60] In fact, all $c_{ij}$ cannot be zero, since we showed earlier that $c_{KZ} - c_{ZZ} = -1$.

The effect on output price also depends on whether $_u$ is greater than or less than one. The sign of the last term (– ) is definitely negative; this "direct effect" means that a lower raises the cost of production (and thus raises the breakeven price $p_Y$). The long first term is an indirect effect. Since $_K - {}_L$ has the same sign as $({}_{YK}\,{}_{XL} - {}_{YL}\,{}_{XK})$, this term has the opposite sign of $(1 - {}_u)$. When $_u$ is smaller than one, then a tighter mandate must increase the price of good $Y$. When $_u$ is large, however, the two effects offset. If the indirect effect dominates the direct effect, then a tighter mandate *decreases* the price of the dirty good.[61]

## 2.6. Conclusion

Just like taxes, regulations that restrict emissions affect producer decisions about use of labor and capital, and they thus affect relative factor prices, total production, and output prices. Existing models analyze the distribution of burdens from taxes, but this paper points out that non-revenue raising restrictions also have burdens on the sources side of income through changes in factor prices as well as burdens on the uses side through changes in output prices. Our model is based on the standard two-sector tax incidence model, but with two important modifications. First, we allow one sector to include pollution as a factor of production that can be a complement or substitute for labor or for capital. Second, we look not at taxes but at four types of mandates.

The model in this paper could be extended in any of the many ways that the Harberger model has been extended, for example to consider increasing returns to scale, imperfect competition, international trade, or capital mobility. Future research could consider capital formation, endogenous technology, and uncertainty. The interaction of other types of regulation with environmental policy is likely to be important, especially considering the highly regulated nature of electric utilities. Furthermore, while we interpret the third input $Z$ as emissions, it could also be interpreted as land, as in Mieszkowski (1972). In this case, the model here can be used to analyze land policies

[61] In the $\hat{p}_Y$ equation, for a large indirect effect, suppose $_u$ and $({}_K - {}_L)$ are large. The sector is highly capital intensive. The output effect dominates the capital-subsidy effect, so the tighter mandate means less

instead of environmental policies. With no existing research on this topic at all, however, we thought that this simple model was a good place to start. And even in this simple model, we get some interesting results. First, a mandate may hurt consumers of the clean good more than consumers of the dirty good. Second, we show how a mandate may disproportionately burden either the factor that is a better substitute for pollution or the factor that is a relative complement to pollution. Third, restrictions on the absolute level of emissions differ from restrictions on emissions per unit output or per unit of an input. For example, a restriction on pollution per unit of output has not only an "output effect" that burdens any factor used intensively in production, but also an "output-subsidy effect" that encourages output to help satisfy the mandated ratio. Similarly, a restriction on pollution per unit capital creates a "capital-subsidy effect" that increases demand for capital and thus raises the rental rate.

An implication is that researchers need to be careful about the nature of an environmental restriction before concluding that it injures the factor used intensively or the factor that is a better substitute for pollution. Those usual effects can be completely offset by other effects we identify in this paper.

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demand for capital. Thus $r$ falls. As seen in the $\hat{r}$ equation, large $_u$ and $(_K - _L)$ mean $r$ falls a lot. The dirty sector is highly capital intensive, so its cost of production and $p_Y$ fall.

**Chapter 3: "Crowding Out of Private Donations and Government Grants: Evidence from Environmental Charities"**

Public goods are often provided by both governments and individuals. Benevolent governments may provide public goods to overcome the market's failure; altruistic individuals may likewise do so. The interaction of these two sources of the provision of public goods ultimately affects the overall level of funding. In response to an increase in government spending on a public good or charity, altruistic individuals who care about the total level of the public good may reduce their contributions. Because of this "crowding-out" effect, a government choosing to increase funding to a charity by a given amount may actually increase the charity's revenues by only a fraction of it. Depending on who moves first, the same effect can occur in the opposite direction. If a government sees that private donations to a charity have risen, then it may reduce its public funds to that charity. For both individuals and governments who are concerned about public goods, the impact of the crowding out effect must be considered.

The literature on crowding out extends back at least to Warr (1982) and Roberts (1984), who show theoretically that an exogenous increase in government funding to charities can decrease private donations. In those models, the crowding out is exactly one-for-one, since the altruistic individuals care only about the total funding to the charity and not the source of funding. Empirical evidence, including Kingma (1989), finds that the crowding out effect is less than one-for-one. One explanation, provided by Andreoni (1989), is that individuals are "impure altruists" in that they receive a "warm glow" from their own giving, independent of the level of the public good. Some studies find crowding *in* of government grants; Khanna and Sandler (2000) find this for charities in the UK, and Payne (2001) finds this for academic research institutions.[62]

[62] More recently, Dokko (2006) finds that changes in government donations to the National Endowment for the Arts after the 1994 Republican electoral victories crowded out private donations to arts groups, Gruber and Hungerman (2005) find that New Deal programs during the Great Depression crowded out church spending on social services, and Simmons and Emanuele (2004) find that government funding can crowd out individuals' donations of both money and time. See also Eckel et. al. (2005), Benzing and Andrews (2004), Andreoni and Payne (2003), and Payne (1998). Steinberg (1990) provides a survey of empirical analyses of charitable giving.

That literature focuses on how government spending crowds out individual giving. This paper examines crowding out in the opposite direction: do private contributions to charities crowd out public funds? Because the direction of the effect depends on which party is the "first mover," I first model the interaction of government and individual donations to a public good. I assume that the government is benevolent and individuals are imperfectly altruistic: they care both about the total level of the public good and about their own contributions. The two groups can move simultaneously, resulting in a Nash equilibrium, or either party can move first, yielding a Stackelberg equilibrium. I then test the model using data on private and public contributions to environmental and social service charities. While social service charities are most commonly examined in the literature, here I also look at environmental charities in order to take advantage of public announcements regarding endangered species and toxic emissions that are used as instruments for private donations to charities.

This paper makes three contributions to the literature on crowding out of charitable contributions. First, though numerous papers test whether government contributions crowd out private contributions, none can be found that either model or empirically test for crowding out in the opposite direction.[63] In fact, a negative correlation between government and private funding of charities could be evidence for either type of crowding out. Here, I test for both types separately by using instrumental variables to control for the endogeneity of the other side's contribution.[64] Second, no study has examined crowding out in the context of environmental public goods. By looking at data on environmental charities, I extend this literature into environmental policy. Third, instead of looking at only a few charities of a particular type, I use an extensive data set with more than 400,000 charities of all types.

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[63] Connolly (1997) studies the relationship between internal and external funding of research at universities using VAR methods. Thus, she generates impulse response functions for both types of funding, in response to an exogenous change in either type. Segal and Weisbrod (1998) use the same methodology to test for direction of causality between total contributions (government and private) and commercial revenues. However, neither paper looks at government and private funding as two separate categories.

[64] Knight (2002) studies the crowding out of state highway spending by federal grants. He develops a model where those federal grants are endogenous and determined by heterogeneous preferences for public goods. This explains the lack of evidence for crowding out in the data. After accounting for endogeneity

In a theoretical model, I find that an exogenous increase in government funding to a public good causes a decrease in individuals' contributions, while an exogenous increase in individuals' contributions causes a decrease in government funding. The size of this crowding out effect is mitigated by the extent that individuals are impurely altruistic. When both of these levels of funding are endogenous, the level of public good provision depends on the order in which the two parties move. If the government moves first, social welfare can be no worse than if donors and the government move simultaneously. Empirically, I look for evidence of crowding out in both directions. However, I find no such evidence. If anything, the data for social service charities suggest that government grants crowd *in* private donations, as in Khanna and Sandler (2000). This may be due to reputation effects created by the government's support.

The presence of crowding out of contributions to charities is of concern to both governments and individuals who make these contributions. A government might choose an optimal level of provision of a charity or public good and adjust its funding to reach that level. Without accounting for the crowding out response by private donors, funding is likely to fall short of the optimal level. Likewise, if the level of private donations affects government support, then an individual's optimal level of giving ought to account for the reaction of government grants. Furthermore, though crowding out of private donations has been studied for social service organizations, the arts, and public radio, the effect is likely to be important in the growing but still unstudied area of environmental charities. How each type of funding affects the other type is crucial to understand if one wants to attain efficiency in the protection of environmental resources.

In the next section I present the theoretical model. In section 3.2, I run simple numerical simulations to quantify the effect that the different formulations of the model have on the level of public good provision and social welfare. Section 3.3 describes the data, and section 3.4 presents the estimation results. Section 3.5 concludes.

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by instrumenting for federal highway grants using data on the political power of state congressional delegations, he does find evidence of crowding out.

### 3.1. Model

The model presented here is a simple static equilibrium model of the amount of private and public giving to a charity or public good. Consider an economy with $N$ individuals indexed by $i$. Each individual has an exogenous income allocation $y_i$ and is subject to a lump sum tax $\tau_i$.[65] The individual gets utility from consumption, $c_i$, from the level of the public good, $G$, and from his or her own private contribution to the public good, $g_i$. This last element of the utility function represents the "warm glow" or "impure altruism" from Andreoni (1989): the individual cares not only about the level of the public good but also about how much he or she personally contributes voluntarily.[66] The utility function is thus $U_i = U(c_i, g_i, G)$. Suppose that $U_x > 0$, $U_{xx} < 0$ for all $x$, and $U_{xy} > 0$ for all $x \neq y$, where $U_x$ represents the derivative of the utility function with respect to the variable $x$. Also suppose that $U_x \to \infty$ as $x \to 0$, assuring an interior solution. The level of the public good is $G = \frac{1}{N}\sum_{i=1}^{N} g_i + \tau_i$, so that private and public contributions to the public good are perfect substitutes in production.[67] The individual's budget constraint is $y_i \geq c_i + g_i + \tau_i$, and this constraint must bind. The individual thus makes a single choice of $g_i$ to maximize $U(y_i - g_i - \tau_i, g_i, \frac{1}{N}\sum_{i=1}^{N}(g_i + \tau_i))$.

The government is benevolent, with a social welfare function equal to a weighted sum of individuals' utilities: $W = \sum_{i=1}^{N} \gamma_i U(c_i, g_i, G)$. The coefficients $\gamma_i$ represent the weight on each individual's utility in the social welfare function. The government chooses the tax structure $\{\tau_i\}$ to maximize social welfare. I now consider six different

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[65] The exogenous income and the lump sum tax mean that issues of the distortionary effects of taxation are not addressed by this model. Saez (2004) considers optimal tax policy in the presence of crowd out and tax distortions. The model here could easily be amended to include proportional taxes rather than lump sum, or it could include a parameter to represent a marginal cost of public funds that captures tax distortions.

[66] A more general utility function, used in Kingma (1989), distinguishes also between other individuals' voluntary contributions and the public provision of the good.

[67] In Ferris and West (2003), the cost of providing the public good differs for public and private contributions. They use this cost-side explanation rather than Andreoni's (1989) utility-based explanation for the partial crowding out of public contributions that is found empirically.

equilibrium concepts for this model to analyze their implications for crowding out in both directions.

### 3.1.1. Exogenous Government Action

First, suppose that the government sets its taxes exogenously and consider the response of individuals. Individual $i$'s problem is:

$\max_{g_i} U(y_i - g_i - \tau_i, g_i, \frac{1}{N}\sum_{j=1}^{N}(g_j + \tau_j))$. Individual $i$ takes as given all other private contributions $g_j$. The first order condition for this maximization problem is $U_c = U_g + (1/N)U_G$. The left hand side of the first order condition is the marginal cost of an additional unit of private contribution, which is the foregone consumption from that unit of wealth, $U_c$. This is equated with the marginal benefit of an additional unit of private contribution, composed of two parts: the "warm glow" from private giving, $U_g$, and the additional amount from the public good that is created from the individual's contribution, $(1/N)U_G$.

Crowding out is analyzed by evaluating $dg_i/d_i$, or the change in private contribution resulting from a change in the forced level of government contribution from individual $i$. This is a comparative static result for an agent's best-response function, not for a Nash equilibrium contribution. This derivative is evaluated using the implicit function theorem:

$$\frac{dg_i}{d\tau_i} = \frac{(-U_{cc} + \frac{1}{N}U_{cG}) - (-U_{gc} + \frac{1}{N}U_{gG}) - \frac{1}{N}(-U_{Gc} + \frac{1}{N}U_{GG})}{-(-U_{cc} + U_{cg} + \frac{1}{N}U_{cG}) + (-U_{gc} + U_{gg} + \frac{1}{N}U_{gG}) + \frac{1}{N}(-U_{Gc} + U_{Gg} + \frac{1}{N}U_{GG})}.$$

This expression is greatly simplified if the utility function does not include a "warm glow" effect. If $g_i$ does not enter the utility function, so that $U_g = U_{gx} = 0$, then $dg_i/d_i = -1$. In this case, private contributions are perfectly one-for-one crowded out by the government's contribution.[68] This result is intuitive; individuals only care about the level

[68] This result is comparable Proposition 3 in Andreoni (1990).

of the public good and not about the source of its funding, so they are indifferent whether it is funded through their voluntary contributions or through their taxes.

Allowing a warm glow effect makes the interpretation of the derivative more complicated. It cannot in general be signed. However, if $U_{gG} \leq NU_{cg}$, then it can be shown that $-1 < \frac{dg_i}{d\tau_i} < 0$. That is, crowding out of the private contribution exists but is only partial. The condition $U_{gG} \leq NU_{cg}$ is sufficient but not necessary. If $U_{gG}$ is too big, then a decrease in government spending on the public good $(G)$ reduces the marginal utility of the warm glow effect $(U_g)$ enough so that the individual reduces his or her private giving.

The asymptotic behavior of this equilibrium also presents clear results. As $N$ • •, the value of crowding out $dg_i/d_i$ • $(-U_{cc} + U_{cg}) / (U_{cc} - 2U_{cg} + U_{gg})$. This expression is strictly between –1 and 0, indicating partial crowding out. As the number of individuals becomes infinitely large, the value of one individual's contribution to $G$ is negligible. Therefore, each person only considers the tradeoff between consumption and warm glow, disregarding any impact that his donation has on the total amount of the public good. Hence, a tax increase provides only a negative income effect. The individual will buy less consumption and warm glow (hence $dg_i/d_i < 0$) and will smooth out the lost income over both of those goods (hence $dg_i/d_i > -1$).[69] While asymptotic behavior can be considered in each of the other equilibria below, none provide additional intuition.

### 3.1.2. Exogenous Individual Action

The previous section assumes that the taxes are set exogenously and considers the response of individuals to a change in those taxes. This structure of the problem is most commonly seen in the empirical literature on crowding out. However, one may just as easily consider the government's response to a change in private donations to public

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[69] In the same model Ribar and Wilhelm (2002) find that as $N$ approaches infinity, crowding out can become either partial, one-for-one, or zero, depending on the parameters of the model. However, this only holds in the more generalized case where government funding of the public good is exogenous and not

goods. Suppose, for example, that a major hurricane kills or displaces thousands of people. Then a large spike in private donations to charities may cause the government to reduce its giving to those charities compared to what it otherwise would have given them under the same disaster conditions but without the increased private contributions.

To capture this other direction of crowding out, suppose that the actions of each individual are treated as exogenous by the government, who then sets the taxes { $_i$} to maximize social welfare. Suppose further that the government sets an identical tax on every individual.[70] The government's problem is

$$\max_{\tau} \sum_{i=1}^{N} \gamma_i U[y_i - g_i - \tau, g_i, \frac{1}{N} \sum\nolimits_{j=1}^{N} (g_j + \tau)],$$

where private giving $g_i$ is exogenous. Assume an interior solution for .[71] This yields the first order condition $\sum_{i=1}^{N} \gamma_i (-U_c + U_G) = 0$. The social marginal cost of increasing the tax on individual $i$ is the foregone value of consumption for that person. This equals the marginal benefit of increasing the tax, which is the value of the increase in the public good. This benefit accrues to each person's utility function, and hence it is summed over *N*. Use the implicit function theorem to calculate the change in the optimal tax in response to a change in private donations:

$$\frac{d\tau}{dg_i} = \frac{\gamma_i (-U_{cc} + U_{cg} + U_{cG} - U_{Gg}) + \frac{1}{N} \sum_{j=1}^{N} \gamma_j (U_{cG} - U_{GG})}{\sum_{j=1}^{N} \gamma_j (U_{cc} - 2U_{cG} + U_{GG})}.$$

The denominator of this expression is strictly negative. With no warm glow effect, the numerator is strictly positive, which implies that private donations crowd out public

subject to a budget constraint. When that constraint is added, crowding out can no longer be zero (see their Corollary 1.2).

[70] The most general form of the tax allows for the government to set a different tax for each individual. However, this generality makes the evaluation of derivatives difficult. To evaluate $d\ /dg_i$ using the implicit function theorem, one must calculate the inverse of an $N \times N$ matrix (from the $N$ first order conditions).

[71] The condition on the utility function mentioned earlier is that $U_x$ • • as $x$ • 0, to ensure an interior solution for $g_i$ in the individual's problem. This does not ensure an interior solution for , however, since is not an argument of the utility function.

spending.[72] In fact, as long as $U_{gG} < U_{cG}$, crowding out must occur. This condition is similar to that in the last section. Again, crowding out must occur as long as the marginal utility from the public good $(U_G)$ does not increase too much in the level of the warm glow effect $(g)$. If so, then a reduction in private giving by individual $i$ may reduce everyone's utility from the public good by enough so that the optimal tax decreases as well.

### 3.1.3. Simultaneous Move (Nash) Equilibrium

The previous two sections have each considered a case where one side of the market acts exogenously. In the following four equilibria, I assume that the actions of both the government and the individuals are endogenous.[73] The differences between these equilibria arise from the order of the movements of the players. In this section, suppose that all of the individuals and the government move simultaneously. This results in a Nash equilibrium. Since both the government and each individual acts as though the other's action is fixed at the equilibrium level, the maximization problems and the first order conditions for each party are identical to the ones in the previous two sections. Thus, the first order conditions are a system of $N + 1$ equations: $\sum_{i=1}^{N} \gamma_i (-U_c + U_G) = 0$ for the government's problem (assuming again a single tax ) and $U_c = U_g + (1/N)U_G$ for each individual $i$.

The first order conditions can be solved to find an expression for  and for $\{g_i\}$. Even with the simplification that the government sets only one tax, however, this is a large system of equations that is impossible to solve without parameterizing the utility function. In addition, one can calculate neither $dg_i/d$  or $d\ /dg_i$, since both the tax level

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[72] Finding conditions for when crowding out is one-for-one is not appropriate in this context, since the tax rate applies to each individual. If individual $i$ increases his or her private contribution by one dollar, then a decrease of one dollar in the tax  would actually decrease the total amount of the public good by $(N - 1)$ dollars.

[73] This is similar to the contribution made by Knight (2002) to the federalism literature. He departs from the assumption of exogenous federal grants to states by supposing that they are determined in a political process, so that federal spending may help determine state spending, and vice versa. However, he does not study charitable giving.

and the individual contributions to the public good are endogenous. The derivatives that were evaluated in the last two sections cannot be evaluated here.

### 3.1.4. Government First Mover (Stackelberg) Equilibrium

Again, suppose that all parties' moves are endogenous, but now suppose that the government moves first, followed by all individuals moving simultaneously. The maximization problem and first order condition for each individual is the same as in section 3.1.1, since individuals are second movers and take the government's action as exogenous. The government, however, chooses both the tax and the individuals' private donations, subject to the individuals' maximizing behavior. The government's problem is thus

$$\max_{\tau, g_i} \sum_{i=1}^{N} \gamma_i U[y_i - g_i - \tau, g_i, \frac{1}{N}\sum_{j=1}^{N}(g_j + \tau)] \text{ such that } -U_c + U_g + (1/N)U_G = 0 \ \ \forall i \, .$$

The constraints are the first order conditions from all of the individuals' maximization problems. Assuming an interior solution for  , the first order conditions for this problem are

$$\sum_{i=1}^{N} \gamma_i (-U_c + U_G) + \sum_{i=1}^{N} \lambda_i (U_{cc} - U_{cG} - U_{gc} + U_{gG} + \frac{1}{N}(-U_{cG} + U_{GG})) = 0 \, ,$$

$$\begin{aligned} &\gamma_i (-U_c + U_g) + \frac{1}{N}\sum_{j=1}^{N} \gamma_j U_G + \frac{1}{N}\sum_{j=1}^{N} \lambda_j (-U_{cG} + U_{gG} + \frac{1}{N} U_{GG}) \\ &+ \lambda_i (U_{cc} - 2U_{cg} + U_{gg} + \frac{1}{N}(-U_{cG} + U_{gG})) = 0 \end{aligned} \quad , \forall i$$

where $_i$ is the Lagrange multiplier for the *i*th constraint. The first equation is the first order condition for the government's choice of  . The first summation on the left is identical to the first order condition from the government's problem when individual's private contributions are exogenous. Before, when just that first summation was set to zero, the interpretation was that the government should set the sum of marginal benefits equal to the sum of marginal costs. The second part of the equation comes from the government factoring in how its decision affects the individuals' optimal decisions. This sum is negative, as long as $U_{gG}$ is not too large. Therefore, the government chooses a tax level   such that the sum of marginal costs is greater than the sum of marginal benefits, when those sums neglect to factor in the individuals' actions. That is, the tax level is higher than it would have been had the government not considered individuals' responses.

In the second equation, the first two parts (those without the $_i$ coefficients) represent how the government would choose $g_i$ to maximize weighted social utility. The government knows that individuals are optimizing, and the rest of these first order conditions contain the individuals' first order conditions from their maximization problems. These $N+1$ equations, along with the $N$ constraints from the individuals' problems, make a system of $2N+1$ equations with $2N+1$ unknowns ( , $\{g_i\}$, and $\{ _i\}$). As in the previous section, the complexity of this system of equations precludes analytical evaluation of derivatives.

### 3.1.5. Individual First Mover (Stackelberg) Equilibrium

Suppose now that the government sets the tax *after* all of the individuals have chosen their level of private contributions. In the first stage, all $N$ individuals move simultaneously, and in the second stage the government moves. The government's maximization problem and first order condition is the same as in the case where individuals' actions are exogenous, since they are given at the time of the government decisions. The individuals must each choose a level of private contribution knowing that it affects the government's choice of tax. Individual $i$'s maximization problem is

$$\max_{g_i,\tau} U(y_i - g_i - \tau, g_i, \tau + \frac{1}{N}\sum_{j=1}^{N} g_j) \text{ such that } \sum_{j=1}^{N}\gamma_j(-U_c + U_G) = 0 .$$

The constraint is the government's optimization condition. Individual $i$ chooses subject to the constraint but can only affect   insofar as $g_i$ is changed. Letting the Lagrange multiplier of this constraint equal $_i$, the first order conditions for individual $i$ are:

$$-U_c + U_g + (1/N)U_G + \eta_i[\gamma_i(U_{cc} - U_{cg} - U_{cG} + U_{gG}) + \frac{1}{N}\sum_{j=1}^{N}\gamma_j(-U_{cG} + U_{GG})] = 0$$

$$-U_c + U_G + \eta_i[\sum_{j=1}^{N}\gamma_j(U_{cc} - 2U_{cG} + U_{GG})] = 0 .$$

The first three terms in the first equation $(-U_c + U_g + (1/N)U_G)$ were found to sum to zero in the prior case where the tax was exogenous. The term with the Lagrange multiplier $_{i}$ shows how the individual's action impacts the government's tax. The first two terms in second equation $(-U_c + U_G)$ would be set to zero if the individual were free to choose the optimal tax level, but the individual is constrained by the government's actions. The term with the Lagrange multiplier is negative, indicating that the marginal benefits of an additional unit of tax $(U_G)$ is set greater than its marginal cost $(U_c)$. Once again, though the first order conditions are relatively easy to find, any further analysis of this equilibrium is impossible without assuming any form on the utility function.

### 3.1.6. First Best Solution

Finally, I evaluate the social planner's problem, where each individual's level of private contribution and the tax are set simultaneously by one party. In this case, a simple intuitive result is found: the optimal tax level is zero. Private and public contributions are perfect substitutes in the production of the public good, so individuals are indifferent as to the source of funding in the part of their utility that is received from the level of the public good $(G)$. However, private and public contributions are not perfect substitutes in individual utility. Individuals receive a positive contribution to utility from their private contributions. Therefore, for any level of the public good, the optimal way of funding it is entirely through private contributions.[74]

Given this fact, the social planner's problem reduces merely to a choice of each individual's level of private contribution $g_i$ to maximize social welfare:

$$\max_{\{g_i\}} \sum_{i=1}^{N} \gamma_i U(y_i - g_i, g_i, \frac{1}{N}\sum_{j=1}^{N} g_j).$$

[74] To speak of voluntary private contributions in the context of the social planner's problem is somewhat misleading. If a social planner really could force each individual's $g_i$, they would not be voluntary contributions at all. Rather, the purpose of evaluating the solution to the social planner's problem is to compare the first best results to the coordination failures of the other equilibria. This model does not consider government subsidization of private donations, but Andreoni (1990) shows that subsidies always Pareto dominate taxes.

The first order conditions for this problem are $\gamma_i U_g + \frac{1}{N}\sum_{j=1}^{N}\gamma_j U_G = \gamma_i U_c$ for all $i$. The marginal cost of an additional unit of $g_i$ is the right hand side, the (weighted) lost consumption of individual $i$. The marginal benefit is the left hand side, the (weighted) utility from the warm glow of the individual contribution plus the utility from the public good. The former is accrued only to individual $i$, while the latter is accrued to all individuals. This equation is a modified version of the Samuelson condition for the optimal provision of a public good.

Each of the first order conditions contain a common term: $\frac{1}{N}\sum_{j=1}^{N}\gamma_j U_G$. By solving for this term, a series of equations is reached: $\gamma_i (U_g - U_c)_i = \gamma_j (U_g - U_c)_j$ for all $i, j$. For clarity, here I have included the subscripts $i$ and $j$ after the difference in the marginal utilities to indicate that the marginal utilities are for different individuals. Define the "private net marginal cost" of an additional unit of $g$ to mean the cost in foregone consumption less the benefit from the warm glow, but not counting the public benefit of the increase in the level of the public good. The equation above says that the weighted private net marginal cost of an additional unit of $g$ for any one individual $i$ must equal the same weighted private net marginal cost of an additional unit of $g$ for any other individual $j$. These weighted private net marginal costs must be equal for all individuals because they must all equal the social marginal benefit of the additional unit of the public good.

**3.2. Numerical Simulations**

Though the first order conditions presented above for the various types of equilibria provide some intuition for comparison, they do not provide tractable solutions for either the government's or individuals' response functions. It is difficult to compare results across the different equilibria. Therefore, in this section, I parameterize the economy and numerically solve the problem for each equilibrium. By finding the tax rate and the level of the social welfare function in each case, I can determine which equilibrium comes closest to the first best, and how that answer varies with the choice of parameterization.

I assume that the number of individuals in the economy, $N$, equals 100. This is large enough to ensure that each individual's marginal effect of a contribution to the public good is small, as is the case for most public goods in reality, though small enough to keep the optimization routine from being excessively computationally intensive. For simplicity, I assume homogeneous individuals. This means that income is the same for all agents (I set this value to one) and that all individuals are equally weighted in the social welfare function. This reduces the number of equations to solve and greatly reduces the numerical complexity of the problem.

Finally, the utility function $U(x,g,G)$ must be specified. I allow this function to have a constant elasticity of substitution, so that $U = ( \ c + \ g + (1 - \ - \ )G \ )^{1/}$. Then, I vary , , and to see how those values affect the outcomes. The first two parameters represent the weight on each component of the utility function. When is much higher than $1 - \ -$ , the warm glow effect is more important than the altruistic effect. The last parameter, , represents the curvature of the utility function. The elasticity of substitution is $= 1/(1 - \ )$. When approaches zero, $= 1$ and the utility function is Cobb-Douglas. The literature does not provide any evidence for what values these parameters might take. However, many papers have estimated the magnitude of the government crowd out effect (as in section 3.1.1). Kingma (1989), for example, finds that a \$10,000 increase in government funding of a public radio station results in a reduction of private donations of \$1,350. Thus, the fraction of crowd out is 13.5%. Payne (1998) finds crowding out at a rate of 50%. For any choice of the parameters , , and I can evaluate the level of crowding out. This level corresponds to the expression for $dg/d_{\ i}$ in the first version of the model in section 3.1.1 above. This is because these previous models have looked at individuals' responses to a change in government funding of charities, which is what that section considers. Thus, for any choice of parameters I can evaluate $dg/d_{\ i}$.

Even specifying a CES utility function and assuming identical agents, the system of equations cannot be explicitly solved. However, as approaches zero and the utility function becomes Cobb-Douglas, some analytical solutions can be found. In the first best case, the tax equals zero and the level of private donations for the representative agent $g = y(1 - \ )$. In the Nash equilibrium case, the solution is piecewise because of the corner solution. If $\ < 1 - \ - \ (N-1)/N$, then $g = y\,(N/(N-1))\,(\ /(\ -1))$ and $\ = y/(1-\ )\,(1 - \ - \ - N\ /(N-1))$. Otherwise, $g = y(1 - \ - \ + \ N)/(N(\ + \ ) + (1 - \ - \ ))$ and $\ = 0$. For the Stackelberg equilibrium where individuals move first, the solutions are the same as the Nash equilibrium solutions. Finally, for the Stackelberg equilibrium where the government is the first mover, an analytical solution cannot be found, and the results are available only numerically.

The results from these simulations are presented in Table 3.1. The first three columns are the utility function parameters that are varied. The fourth column lists the level of the crowd out effect measured by $dg_i/d\ _i$ for those parameters. With each set of parameters, I find the first best solution, and the equilibrium outcome under the Nash and the two Stackelberg equilibria. For each type of equilibrium, Table 3.1 lists the tax and the ratio of the social welfare from that equilibrium to the social welfare in the first best solution. This ratio indicates how close that equilibrium comes to reaching the first best. It can never be greater than one, since none of these equilibria by definition can achieve a higher social welfare than the first best solution. I do not present the tax in the first best solution, since it is always zero, as proved above.

**Table 3.1**

**Numerical Simulations**
$y_i = 1$ and $_i = 1$ for all $i$
$N = 100$

| Parameters | | | | Nash | | Stackelberg – Govt. Moves First | | Stackelberg – Agents Move First | |
|---|---|---|---|---|---|---|---|---|---|
| = 0 (Cobb Douglas) | | | | | | | | | |
| | | 1 – – | Crowd out | *Nash* | $SWF_{Nash}$/ $SWF_{Best}$ | *GovFirst* | $SWF_{GovFirst}$/ $SWF_{Best}$ | *IndFirst* | $SWF_{IndFirst}$/ $SWF_{Best}$ |
| 0.5 | 0.3 | 0.2 | -0.378 | 0 | 0.9690 | 0 | 0.9690 | 0 | 0.9690 |
| 0.5 | 0.4 | 0.1 | -0.446 | 0 | 0.9939 | 0 | 0.9939 | 0 | 0.9939 |
| 0.5 | 0.1 | 0.4 | -0.170 | .3322 | 0.8660 | .2771 | 0.8697 | .3322 | 0.8660 |
| 0.9 | 0.075 | 0.025 | -0.077 | 0 | 0.9966 | 0 | 0.9966 | 0 | 0.9966 |
| 0.9 | 0.025 | 0.075 | -0.028 | .0510 | 0.9698 | .0488 | 0.9698 | .0510 | 0.9698 |
| 0.9 | 0.001 | 0.099 | -0.001 | .0981 | 0.9954 | .0980 | 0.9954 | .0981 | 0.9954 |
| = 0.5 | | | | | | | | | |
| 0.5 | 0.4 | 0.1 | -0.392 | 0 | 0.9881 | 0 | 0.9881 | 0 | 0.9881 |
| 0.5 | 0.1 | 0.4 | -0.039 | .3654 | 0.8609 | .3453 | 0.8612 | .3654 | 0.8609 |
| = -0.5 | | | | | | | | | |
| 0.5 | 0.4 | 0.1 | -0.464 | 0 | 0.9960 | 0 | 0.9960 | 0 | 0.9960 |
| 0.5 | 0.1 | 0.4 | -0.258 | .2783 | 0.8855 | .2110 | 0.8922 | .2779 | 0.8857 |

*Notes*: Utility functional form is constant elasticity of substitution, where is the weight on consumption, is the weight on the warm glow, and 1 – – is the weight on the public good. The value of "Crowd out" is the value taken by $dg/d_i$ from section 3.1.1. The tax in the first best solution always equals zero. The values in the columns are the tax levied in that equilibrium. The values in the $SWF_x/SWF_{Best}$ columns are the ratios of the value of social welfare in that equilibrium to the value in the first best.

Half of the cases in Table 3.1 result in a corner solution, where the tax rate equals zero. Without the constraint that the tax must be non-negative, the equilibrium outcome would result in a negative tax in many cases. This is because of the warm glow effect: since individuals get utility from their own giving, governments may subsidize that giving via the tax, thereby increasing social welfare. The tax is more likely to be zero when the utility from warm glow is high relative to the utility from the public good (rows one, two, and four). On the other hand, when the altruism effect is higher than the warm glow effect, governments must set a tax to overcome the coordination failure arising from the public good (rows three, five, and six). Social welfare in the Nash equilibrium can never exceed that in the equilibrium where government is the first mover, because the government moving first can always choose the same action as in the Nash equilibrium.

Finally, in most cases the value of social welfare in the equilibrium is very close to that of the first best. Among the Cobb-Douglas cases, the only instance where the ratio of welfares is less than 95% is in row three, where the altruism effect is the largest. The explanation is that the altruism effect, coming from the public good, leads to a free rider problem, whereas the warm glow effect, which is not a public good, does not.

The last four simulations in Table 3.1 show how departing from a Cobb-Douglas utility function affects the results. I allow to equal 0.5 or -0.5, and choose two sets of values of and (taken from rows two and three). The patterns when comparing the three equilibria are similar. Finally, in all of the simulations with a zero tax, the value of social welfare is identical under all three equilibria. When the government's best response is constrained at setting the tax to zero, the individuals react the same way to that tax regardless of the order in which they move. Even when they are the first movers, any marginal change in the value of donations does not affect the government's response, which is flat at zero.

### 3.3. Data

The data on nonprofit environmental organizations comes from IRS tax returns filed by eligible organizations. These data are collected and distributed by the National Center for Charitable Statistics (NCCS) at the Urban Institute.[75] They are based on the Form 990 that must be filed by certain 501(c)(3) nonprofit organizations. These forms must be filed by all eligible organizations, except for religious organizations and all those with less than $25,000 in gross receipts.[76] These data from 1998-2003 are contained in the Guidestar-NCCS National Nonprofit Database, which contains 1,388,480 observations.

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[75] http://nccs.urban.org.

[76] The exclusion of religious organizations is likely significant, since they receive over half of all charitable giving in the United States (Ronsvalle and Ronsvalle, 2001). Religious organizations that receive the majority of their revenue from serving the general public are required to file Forms 990. These include the Sisters of Mercy hospital chain and Lutheran Social Services. About 15,000 such religious organizations were required to file in 2001. Examining donations to Presbyterian Church congregations, Hungerman

Organizations are classified in the dataset according to the National Taxonomy of Exempt Entities (NTEE), a system developed by the NCCS. The NTEE divides charities into 645 centile level codes, collapsible into 26 major groups and 10 major categories. I focus on charities classified into major groups C and D, representing "Environment" and "Animal-Related," respectively. Environmental charities are defined as those groups whose primary purpose is to preserve, protect and improve the environment. Animal-related charities are defined as private non-profit organizations whose primary purpose is to provide for the care, protection and control of wildlife and domestic animals that are a part of the living environment; to help people develop an understanding of their pets; and to train animals for purposes of showing.[77] Hereafter, I refer to all of these charities as environmental organizations.

I compare the results based on data from environmental organizations to results based on a set of other types of social service organizations. This set includes organizations that focus on: crime, employment, food and nutrition, housing, human services and community improvement.[78] This set of organizations, hereafter referred to as social service organizations, provides a basis to see how the environmental organizations differ.

The differences in charities' revenue sources can be seen in Figure 3.1, which divides up the average source of funding for each type of charity into several categories.[79]

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(2005) finds that government provision of charitable services crowd out church donations by 20-38 cents on the dollar.

[77] Specifically, environmental charities include those involved in pollution control and abatement; conservation and development of natural resources; control or elimination of hazardous or toxic substances including pesticides; solid waste management; urban beautification and open spaces development; environmental education and outdoor survival; and botanical gardens and horticultural societies. Animal-related charities include organizations that develop and maintain fisheries resources and wildlife habitats to preserve and protect endangered species and other wildlife; humane societies; veterinary services; aquariums; and zoos.

[78] These are the organizations listed under the 1-digit NTEE codes of I, J, K, L, P and S. This is the same set of codes used by Andreoni and Payne (2003) for their set of social service organizations. Here, I separate environmental charities from the rest of the group. Andreoni and Payne (2003) also exclude some organizations that they describe as not directly providing services, while I include all 501(c)(3) organizations in those categories (see their fn 15).

[79] The first category is direct public support, which is the main category of donations from individuals. Second is indirect public support, comprised mainly of donations given to the charities collected by federated fundraising agencies, such as the United Way. The next category is government grants. Program service revenue is the money collected from the services that form the organizations exemption from tax.

The revenue sources for the two types of charities are dramatically different. Environmental charities receive half of their revenue from direct public support, including individual donations, while social service charities receive only 14% from this source. Government grants constitute a much smaller share of environmental charities' revenues (11%) than of social service charities' revenues (26%). Social service charities get about half of their revenue from program services; environmental charities receive only one-fifth of their revenues from this source.[80] The remaining sources of revenues are small for both types of charities, though environmental charities receive more in each of the remaining categories.

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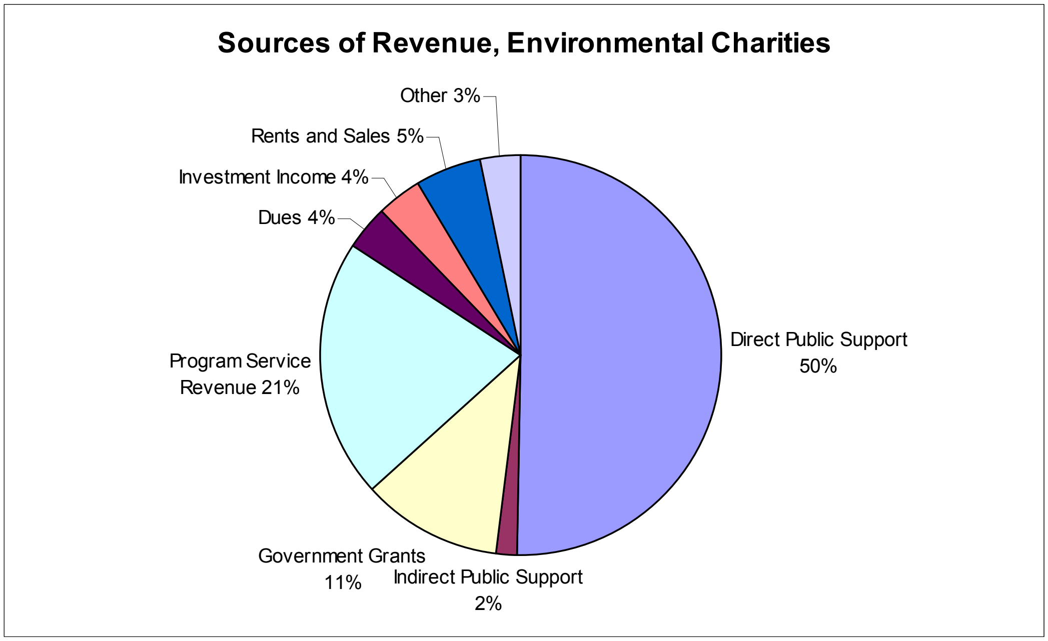
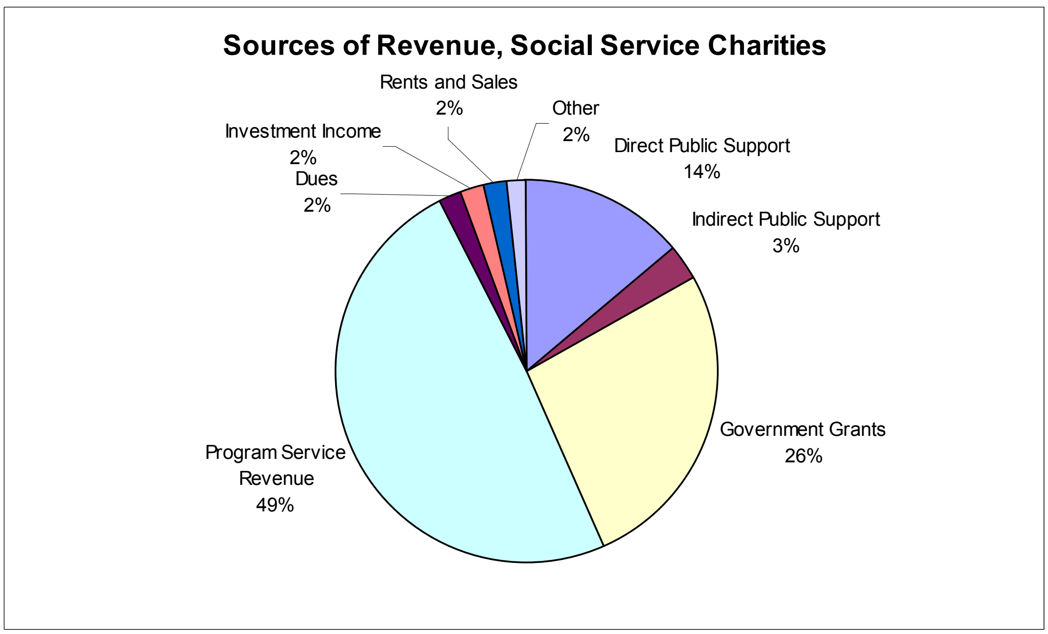
For example, a hospital would count as program service revenue all of its charges from medical services or room charges. Dues collected includes only the amount of dues received that are not contributions, for example the dues that go towards a subscription to a newsletter or some other benefit. Investment income includes dividends and interest on savings and cash accounts; rents and sales include net revenue from rents and from sales of securities, inventory, or other assets. Finally, the last category includes all other revenue, including from special events such as dinners, raffles, or door-to-door sales of merchandise.

[80] Segal and Weisbrod (1998) test for crowding out between all donations, including private and government grants, and program service revenue.

**Figure 3.1**




*Notes*: Environmental charities include those in NTEE codes C (Environment) and D (Animal-related). Social service charities include those in NTEE codes I (Crime and Legal-related), J (Employment), K (Food, Agriculture, and Nutrition), L (Housing and Shelter), P (Human Services), and S (Community Improvement and Capacity Building). Investment income includes interest and dividends; rents and sales includes securities and inventory; other includes special events revenues. Values are total dollar amounts from 1998-2003 in constant 2002 dollars.

Table 3.2 presents revenues aggregated into four main categories. As a measure of private donations, I combine direct public support, indirect public support, and dues. Government grants and program service revenue have their own categories, and the remaining revenues are classified as "other." The top panel of Table 3.2 lists statistics for environmental organizations, the bottom panel for social service organizations. The number of environmental organizations is about one-fifteenth the number of social service organizations. On average, environmental organizations receive less total revenue than social service organizations ($978,000 vs. $1,716,000). Of this revenue, though, they receive a great deal more from private donations, and less from government grants and program service revenue. Finally, the mean values are all much higher than the median values, suggesting a data set that is skewed towards high-revenue firms. For additional information, the 75th percentile value of each variable is listed. These statistics suggest that the revenue sources for environmental charities are quite different than those of social service charities.

**Table 3.2**

| Summary Statistics – Charity Revenues | | | | | | |
|---|---|---|---|---|---|---|
| | Number of Observations | Number of Organizations | Mean ($1,000s) | Standard deviation ($1,000s) | Median ($1,000s) | 75th percentile ($1,000s) |
| Environmental Organizations | 50,111 | 12,741 | | | | |
| Private Donations | | | 543 | 6230 | 46 | 186 |
| Government Grants | | | 112 | 1074 | 0 | 0 |
| Program Service Revenue | | | 204 | 2654 | 1 | 48 |
| Other Revenue | | | 119 | 1603 | 7 | 33 |
| Social Service Organizations | 391,574 | 89,806 | | | | |
| Private Donations | | | 322 | 4510 | 22 | 145 |
| Government Grants | | | 452 | 3243 | 0 | 103 |
| Program Service Revenue | | | 845 | 8774 | 34 | 303 |
| Other Revenue | | | 97 | 1254 | 6 | 35 |

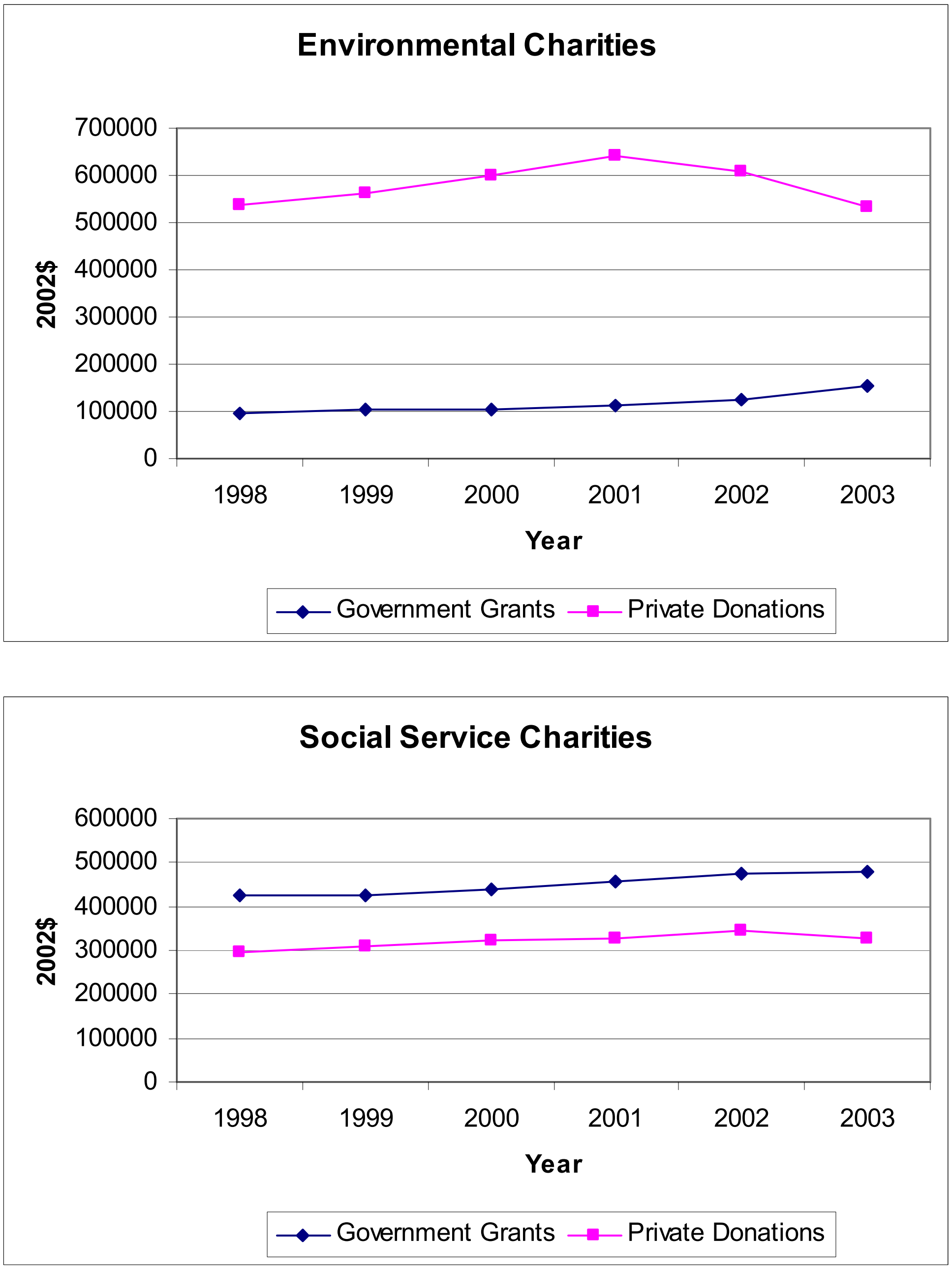
*Notes*: Data are averaged over 1998-2003 in constant 2002 dollars. Private donations include direct and indirect public support and dues. Other revenue includes interest, rents and sales.

Recent trends in these values are presented in Figure 3.2. The top panel is for environmental charities; the bottom panel for social service charities. The values presented are the average per charity value of government grants and private donations in constant 2002 dollars. Just as shown in Table 3.2 for 2002 only, environmental charities receive more from private donations than from government grants, while social service charities receive more from government grants in all years.

The presence of crowding out in either direction implies that spikes in government grants would be accompanied by dips in private donations, and vice versa. For social service charities, no such pattern emerges, since both values appear to be increasing. However, environmental charities exhibit this pattern. After 2001, a dip in private donations is accompanied by an increase in government grants.[81] This is merely suggestive, so I turn to regression analysis to identify the presence of a crowding out effect.

[81] The dip in private donations to environmental charities approximately coincides with the early 2000s recession. The fact that a similar dip is not visible in private donations to social service charities may indicate that donations to environmental charities are more income elastic than donations to social service charities.

**Figure 3.2**




*Notes*: Environmental and Social Service charities are defined as in Figure 3.1. All dollar values are deflated by CPI.

### 3.4. Econometrics

I test two predictions from the model above. The first is that an increase in government grants to a charity leads to a decrease in private donations. The second prediction is that an increase in private donations to a charity reduces the amount of government grants that it receives. The first prediction has been tested in other papers and has found mostly positive support.[82] The second prediction is unique to this paper. Also, I test for these predictions separately in environmental charities and social service charities. While other papers have looked at social service charities and some other categories of charities, no paper has specifically tested for crowding out effects in environmental charities.

Because of the two predictions, I must run two separate regressions, one in which the level of private donations to a charity is the dependent variable and the level of government grants is an independent variable, and one with those two variables reversed. The level of private donations is defined as in Table 3.2 above: the sum of direct public support, indirect public support, and dues. I also add control variables to the regressions. At the charity level, these are the level of program service revenues and all other revenues, along with the fraction of a charity's expenditure that is spent on fundraising. I expect that more money spent on fundraising would increase the level of private donations. Finally, an indicator variable for charity type is included. The environmental data set has 40 charity types, based on the NTEE centile level codes, and the social service set has 6, based on the NTEE 1 digit code. Furthermore, I include a number of state-year level variables to control for economic, demographic, and political conditions. These are the unemployment rate, average household income, total population, fraction of the population 65 or older, the fraction of a state's US Congress and Senate delegations that are Democrats, and a dummy for whether the state governor is a Democrat. Political and economic variables may have important effects on the levels of both private and public contributions to charities. A state with a higher proportion of Democrats in power is likely to be composed of more liberal citizens who may be more willing to provide

[82] An exception is Khanna and Sandler (2000), who find crowding *in* of private donations by government contributions, using data from UK charities.

financial support for environmental charities. Likewise, Democratic congresses may be more willing to approve higher levels of funding for these groups. If so, leaving out political proxies causes an upward bias on the coefficient of interest. Finally, because I have six years of data from thousands of organizations, I am able to control for organization-specific unobservable effects using panel data econometric methods.[83]

A number of measures are taken to clean the data. Some charities report revenues by category (e.g. private donations, government grants) that do not add up to the reported level of total revenues. Likewise, for some charities the expenditures do not add up correctly. I eliminate all of these charities from the data set (about 20% of observations from the social service charity data set and 30% from the environmental charity data set). Though the data are a panel, it is a very unbalanced one. To compensate, I include in the regressions only those charities which appear for all six years (about 40% of the charities).

Estimates are likely to suffer from endogeneity bias. Charities jointly determine the amount of private donations and government grants that they solicit. Unobservable effects may lead to an increase in both of these simultaneously, biasing the coefficient estimates upwards. For example, an exogenous event may increase the need for a particular charity, which would increase that charity's private donations and government grants. Alternatively, endogeneity could bias the estimates downwards. A restructuring of the charity or of its nonprofit status could cause it to reallocate its funding between donations and grants, which would create a negative correlation between these two values not due to crowding out.

Instrumental variables regression is used to correct the endogeneity bias. This requires two separate sets of instruments: one to instrument for the level of government grants in the determination of private donations and one for the level of private donations in the determination of government grants. The literature provides numerous examples of the first set of instruments, since this direction of crowding out has been tested before.

[83] The model here does not consider the behavior of the charity in response to changes in government grants, like the fundraising models of Andreoni (1998), Andreoni and Payne (2003), and Rose-Ackerman (1987). However, I include fundraising expenditures to control for a charity's efficiency in converting revenues to charitable services (see Khanna and Sandler 2000).

One such set of instruments consists of state-level measures of government transfers to individuals from SSI programs.[84] This represents the overall level of transfers and government giving in a state a particular year. Some states may be more "generous" in their giving, and these instruments should pick that up.[85] I also use the average level of government grants in a state in a year as a predictor.

As an instrument for the level of private donations, I use a measure of the price of a dollar of charitable donation based on the state's income tax and rules for allowing deductions of those contributions. From NBER's Taxsim program, I have the state and federal average marginal tax rate for each state and year in the sample.[86] I also have an indicator as to whether or not the state allows a deduction of charitable contributions for state income tax, as are allowed for federal taxes. From this, I construct a price of giving to charity. I expect that as this price increases, giving to charities in that state decreases, controlling for income, demographic, and political factors.[87]

The results for these instrumental variables, random effects model regressions are presented in Tables 3.3 and 3.4. Table 3.3 presents the results from regressions where private donations are the dependent variable and government grants are the regressor; Table 3.4 presents the results from regressions where these are reversed. The top panel in each table represents the regressions using environmental charities, and the bottom panel represents the regression using social service charities. Each panel of Table 3.3 has seven columns, one for each regression model employed. In the first column are the base case results, using the instruments described.

[84] Khanna and Sandler (2004), Andreoni and Payne (2003), and Payne (1998) use similar instruments.

[85] Though the basic level of SSI benefits is set at the federal level, many states choose to supplement that value. I also used the level of OASDI benefits as instruments, but adding those had no effect on the results, and they were only available for four out of six years in the sample.

[86] See www.nber.org/~taxsim.

[87] Randolph (1995), Auten, Sieg, and Clotfelter (1998) and Stuntz (2006) all find that the tax deduction significantly affects the amount of giving. Andreoni (2005) reviews this literature.

**Table 3.3**

| The Determinants of Private Donations [a] | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Environmental Charities** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** |
| Government Grants [b] | .265<br>(.177) | .209<br>(.476) | .148<br>(.204) | .427**<br>(.145) | .122<br>(.107) | 1.40<br>(1.41) | .439<br>(.730) |
| Program Service Revenue | .207**<br>(.0188) | .215**<br>(.0206) | .213**<br>(.0203) | .169**<br>(.0229) | .254**<br>(.0269) | .0881<br>(.126) | .150<br>(.116) |
| Other Revenue | .0829**<br>(.0164) | .120**<br>(.0179) | .112**<br>(.0182) | .129**<br>(.0189) | .150**<br>(.0241) | .144**<br>(.0321) | .0590<br>(.0446) |
| Fraction of Expenditure for Fundraising (Thousands of dollars) | 701**<br>(87.9) | 741**<br>(93.0) | 723**<br>(91.7) | 637**<br>(92.5) | 1010**<br>(170) | 335**<br>(58.0) | 742**<br>(99.4) |
| Number of Observations | 16585 | 13823 | 13823 | 14349 | 7982 | 13407 | 5632 |
| Number of Charities | 2766 | 2766 | 2766 | 2400 | 1331 | 2389 | 1009 |
| $R^2$ | .0962 | .107 | .108 | .0826 | .1695 | .0088 | .0594 |
| | | | | | | | |
| **Social Service Charities** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** |
| Government Grants [b] | .423**<br>(.0517) | .406**<br>(.0853) | .377**<br>(.0814) | .382**<br>(.0488) | .287**<br>(.0390) | .628**<br>(.0753) | .327**<br>(.0451) |
| Program Service Revenue | .0767**<br>(.00963) | .0765**<br>(.0156) | .0257**<br>(.00533) | .0701**<br>(.00848) | .104**<br>(.0139) | .0879**<br>(.0144) | .0894**<br>(.0141) |
| Other Revenue | .00610<br>(.00457) | .0160**<br>(.00512) | .0146**<br>(.00498) | .00853<br>(.00473) | .00504<br>(.00748) | .0102*<br>(.00466) | .0547**<br>(.00715) |
| Fraction of Expenditure for Fundraising (Thousands of dollars) | 762**<br>(38.3) | 814**<br>(50.3) | 762**<br>(44.0) | 932**<br>(41.1) | 936**<br>(64.7) | 749**<br>(25.8) | 1020**<br>(38.1) |
| Number of Observations | 174209 | 145219 | 145219 | 162855 | 90238 | 151568 | 72616 |
| Number of Charities | 29096 | 29092 | 29092 | 27238 | 15053 | 26210 | 12654 |
| $R^2$ | .0150 | .0165 | .0159 | .0187 | .0310 | .0045 | .0126 |
| **For Both Types of Charities** | | | | | | | |
| Lagged Instruments? | No | Yes | Yes | No | No | No | No |
| Lagged Endogenous Regressor? | No | No | Yes | No | No | No | No |
| Exclude National & Support Organizations? | No | No | No | Yes | No | No | Yes |
| Exclude Charities w/o Grants or Donations? | No | No | No | No | Yes | No | Yes |
| Exclude Top 10% of Revenue? | No | No | No | No | No | Yes | Yes |

[a] Data are from 1998-2003 and only include those organizations that are in the panel for all six years and whose reported categorical revenues sum up to reported total revenues, and likewise for expenses. State-year level controls include population, per capita income, unemployment rate, fraction of individuals older than 65, number of Democratic senators, fraction of US House delegation Democratic, and an indicator for whether the governor is a Democrat.

[b] Instruments for government grants are the state-year average value of grants to charities, the state-year total payments paid to individuals through SSI, and the state-year payments paid to individuals through SSI for the aged.

The coefficient of interest in the regressions in Table 3.3 is that of government grants. The theory suggests that these will be negative, symptomatic of crowding out of government contributions. However, such a result is not found. In the first column, the coefficient for environmental charities is insignificant. For the social service charities, the coefficient is positive. This is evidence for crowding in rather than crowding out, similar to results that have been found by Khanna and Sandler (2000) and Payne (2001). The two other categories of revenue, program service revenues and other revenues, are significantly positively correlated with private donations. Finally, fundraising is also a positive determinant of private donations.

The model of crowding out depends on either governments or individuals being able to respond to the level of giving from the other. Thus, an effect of timing might not be captured entirely in this static model. Therefore, I also use lagged instruments in the first stage in column 2, and lagged values of the endogenous regressor in column 3. These changes do not alter the results by much.

It is also possible that the effect of crowding out as well as the other control variables and instruments are only applicable to a subset of the charities, for three reasons. First, while some of the controls and all of the instruments are at the state-year level, not all of the charities operate only in the state in which they are registered. Many are national organizations that accept donations and possibly government grants from other states. For these charities, the instruments are unlikely to be good predictors. Though I cannot know for certain which organizations are national and which are local, column 4 excludes those whose names begin with "National," "American," or "North American." I also exclude organizations classified as support organizations under the NTEE taxonomy.[88] These organizations do not directly provide services but support organizations or individuals who do provide services through management and technical assistance, fundraising, and public policy analysis. Second, many of the charities receive no government grants throughout the entire six-year sample period, and many receive no private donations throughout the period. Such charities are likely not to receive such funding forms at all, even in response to a change in the other funding source, and thus I also exclude them from the regressions in later columns (5 and 7). Third, Table 3.2 indicates a great deal of skewness in the data. It is possible that the relatively few organizations with very large revenues behave differently and swamp the effects of the majority. Column 6 therefore eliminates from the regression those charities in the top decile of expenditures.

For environmental charities, one of these latter regressions finally provides a significant coefficient for the main regressor in column 4, but it is in the wrong direction (positive). Thus, if anything, the excluded national charities behave more like the theory suggests than the other charities. For social service charities, limiting the sample in this way changes the magnitude of the coefficient but it remains significantly positive.

Table 3.4 presents the regressions in the opposite direction, where the level of government grants is the dependent variable and the level of private donations is the endogenous regressor. The instrument used is the price of a dollar of charitable donation. Column 1 is the base case, columns 2 and 3 are with lagged regressors and instruments, and columns 4-7 limit the sample size as described above. Overall, these regressions are even less illuminating, since the $R^2$ values are lower and fewer of the coefficients are significant. For environmental charities, the coefficient of interest on private donations is never significant, though it is of the expected sign in columns 6 and 7. For social service charities, the value of the coefficient fluctuates greatly, though it is never significant and only negative in column 7.

[88] These are organizations whose last two digits of the NTEE centile code are less than 20.

**Table 3.4**

| The Determinants of Government Grants [a] | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Environmental Charities** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** |
| Private Donations [b] | .228 (.130) | .212 (.162) | .200 (.201) | .177 (.153) | .213 (.0494) | -.0911 (.116) | -.627 (1.07) |
| Program Service Revenue | .00480 (.0309) | .0113 (.0381) | -.00040 0.0381) | .0377 (.0400) | .0494 (.111) | - .0946** (.0138) | -.122 (.0730) |
| Other Revenue | -.0102 (.0592) | .00653 (.0731) | -.0237 (.0462) | .0125 (.0865) | .0554 (.171) | .0110 (.0160) | .00310 (.0343) |
| Fraction of Expenditure for Fundraising (Thousands of dollars) | -700** (269) | -663* (327) | -255 (189) | -588 (302) | -1070 (721) | 41.1 (37.7) | 501 (722) |
| Number of Observations | 16585 | 13823 | 13823 | 14349 | 7982 | 13407 | 5632 |
| Number of Charities | 2766 | 2766 | 2766 | 2400 | 1331 | 2389 | 1009 |
| $R^2$ | .0343 | .0384 | .0337 | .0435 | .0842 | .0123 | .000 |
| | | | | | | | |
| **Social Service Charities** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** |
| Private Donations [b] | 21.2 (41.6) | .0604 (.262) | .0561 (.276) | 7.58 (4.55) | 17.1 (19.7) | 1.89 (7.44) | -.0740 (.257) |
| Program Service Revenue | .162 (.828) | -.291** (.00624) | -.292** (.00214) | -.280 (.150) | -1.12 (1.18) | -.0974 (.105) | -.127** (.00840) |
| Other Revenue | .469 (.959) | - .0294** (.00719) | - .0304** (.00445) | -1.99 (1.27) | -3.50 (4.25) | -.178 (.689) | .125* (.0629) |
| Fraction of Expenditure for Fundraising (Thousands of dollars) | -9040 (17500) | -111 (104) | -93.7* (39.0) | -16700 (9170) | -33600 (36600) | -2290 (7520) | -859 (467) |
| Number of Observations | 174209 | 145219 | 145219 | 162855 | 90238 | 151568 | 72616 |
| Number of Charities | 29096 | 29092 | 29092 | 27238 | 15053 | 26210 | 12654 |
| $R^2$ | .0041 | .0042 | .0042 | .0063 | .0082 | .0013 | .0217 |
| **For Both Types of Charities** | | | | | | | |
| Lagged Instruments? | No | Yes | Yes | No | No | No | No |
| Lagged Endogenous Regressor? | No | No | Yes | No | No | No | No |
| Exclude National & Support Organizations? | No | No | No | Yes | No | No | Yes |
| Exclude Charities w/o Grants or Donations? | No | No | No | No | Yes | No | Yes |
| Exclude Top 10% of Revenue? | No | No | No | No | No | Yes | Yes |

[a] Data are from 1998-2003 and only include those organizations that are in the panel for all six years and whose reported categorical revenues sum up to reported total revenues, and likewise for expenses. State-year level controls include population, per capita income, unemployment rate, fraction of individuals older than 65, number of Democratic senators, fraction of US House delegation Democratic, and an indicator for whether the governor is a Democrat.

[b] Instruments for private donations are the calculated private cost of donations, based upon the state plus federal income tax rate and whether states allow charitable deductions, and the fraction of a charity's revenue devoted to fundraising.

In Table 3.5 I use instruments specific to a particular type of charity to better identify the effect of private donations on government grants. The first instrument used here is the number of species listed as threatened or endangered under the Endangered Species Act (ESA), in a state-year. Listing a species is an early step in the process under the ESA. By listing a species, it becomes illegal to hunt or otherwise harm that species, but no governmental action is taken until possibly a critical habitat for the species is chosen. As of 1998, only 40% of listed species had designated critical habitat.[89] Therefore, listing a species is expected to have no direct effect on government grants to charities that deal with endangered species. However, having a new species listed nearby is likely to promote individuals to donate to charities that deal with that issue. Since the ESA is widely reported in the media individuals are likely to be aware of the new listings.[90] The instruments used are a count of the number of species listed as either endangered or threatened in each state in each year.

The NTEE classification system category "D31" covers charities that deal with "Protection of Endangered Species." Because only a few of these charities (14) appear in the data set in all six years, I also include charities from category "D30": Wildlife Preservation and Protection. These charities are also likely to be impacted by announcements of the listing of endangered species. The results from these regressions appear in Table 3.5. Though the new instrument is expected to identify the effect of private donations on government grants, none of the coefficients on that regressor are significant, and they are all positive. This may partly be due to the fact that so few charities fall into this category, especially in the columns that exclude the broader "D30" designation.

[89] Brown and Shogren (1998).
[90] Hendrickson (2005).

**Table 3.5**

| The Determinants of Government Grants, Wildlife/Endangered Species Charities [a] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Environmental Charities** | **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** | **(8)** |
| Private Donations [b] | .347<br>(.263) | .610<br>(.626) | -.740<br>(2.41) | -<br>.0683<br>(.222) | .527<br>(.375) | .567<br>(.407) | .971<br>(1.14) | .000954<br>(.338) |
| Program Service Revenue | .198<br>(.205) | -.108<br>(.366) | .428<br>(1.12) | .307<br>(.295) | -.114<br>(.118) | -.128<br>(.131) | -<br>.00745<br>(.165) | -.353*<br>(.165) |
| Other Revenue | .0527<br>(.0919) | .186<br>(.194) | -.173<br>(.506) | -.327<br>(.348) | -.124<br>(.0662) | -.128<br>(.0707) | -1.11*<br>(.466) | .308<br>(.439) |
| Fraction of Expenditure for Fundraising (Thousands of dollars) | 71.1<br>(276) | 275<br>(632) | 67.8<br>(625) | -21.4<br>(290) | -755<br>(428) | -822<br>(478) | -198<br>(655) | -503**<br>(145) |
| Number of Observations | 84 | 78 | 36 | 25 | 480 | 462 | 204 | 144 |
| Number of Charities | 14 | 13 | 6 | 6 | 80 | 77 | 34 | 28 |
| $R^2$ | .127 | .0643 | .0463 | .1787 | .266 | .262 | .432 | .0854 |
| | | | | | | | | |
| Category "D30" included? | No | No | No | No | Yes | Yes | Yes | Yes |
| Exclude National Organizations? | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Exclude Charities w/o Grants or Donations? | No | No | Yes | Yes | No | No | Yes | Yes |
| Exclude Top 10% of Revenue? | No | No | No | Yes | No | No | No | Yes |

[a] Data are from 1998-2003 and only include those organizations that are in the panel for all six years and whose reported categorical revenues sum up to reported total revenues, and likewise for expenses. Only charities in categories D30 and D31 are included. State-year controls are identical to those in Tables 3.3 and 3.4.
[b] Instruments for private donations are the price of donations, the fraction of expenses given to fundraising, and the number of species listed as endangered or threatened in a given state that year.

In Table 3.6, I use a different instrument for private donations that applies to a specific set of charities. The Toxics Release Inventory (TRI) is an EPA-sponsored program that publicly releases information on toxic chemicals emitted by individual plants. Businesses and government agencies self-report emissions, which are available on the EPA website.[91] The reported level of emissions does not relate to any regulatory power; they are reported simply to inform the public and allow individuals to make more informed decisions about how pollution impacts their health.[92] Because of this, reported TRI emissions are likely to impact private donations to charities that deal with industrial

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91 http://www.epa.gov/tri/.
92 Bui and Mayer (2003) test if changes in reported TRI emissions affect neighborhood house prices; they find no correlation.

pollution but are unlikely to affect government behavior directly.[93] The NTEE category "C20" covers charities dedicated to "Pollution Abatement and Control"; in Table 3.6 the sample is limited to that subset. As with all of the regressions where the level of government grants is the dependent variable, few of the coefficients are significant. However, in columns 3 and 4, the coefficient of interest is of the expected sign (negative) and is close to being significant at the usual levels.

**Table 3.6**

| **The Determinants of Government Grants, Pollution Abatement and Control Charities [a]** | | | | |
|---|---|---|---|---|
| **Environmental Charities** | **(1)** | **(2)** | **(3)** | **(4)** |
| Private Donations [b] | .191<br>(.408) | .115<br>(.399) | -.253<br>(.604) | -.931<br>(.614) |
| Program Service Revenue | .0643<br>(.0485) | .0677<br>(.0483) | -.0239<br>(.302) | -.0527<br>(.156) |
| Other Revenue | .179<br>(.213) | .196<br>(.213) | .903*<br>(.372) | .627<br>(.775) |
| Fraction of Expenditure for Fundraising<br>(Thousands of dollars) | -653<br>(495) | -634<br>(484) | -1380<br>(888) | 1.21<br>(448) |
| Number of Observations | 444 | 432 | 228 | 170 |
| Number of Charities | 74 | 72 | 38 | 32 |
| $R^2$ | .0008 | .0086 | .168 | .193 |
| | | | | |
| Exclude National Organizations? | No | Yes | Yes | Yes |
| Exclude Charities w/o Grants or Donations? | No | No | Yes | Yes |
| Exclude Top 10% of Revenue? | No | No | No | Yes |

[a] Data are from 1998-2003 and only include those organizations that are in the panel for all six years and whose reported categorical revenues sum up to reported total revenues, and likewise for expenses. Only charities in category C20 are included. State-year controls are identical to those in Tables 3.3 and 3.4. .
[b] Instruments for private donations are the price of donations, the fraction of expenses given to fundraising, and the total emissions reported in the TRI from sources in that state that year.

The outcomes of the variables of interest may be determined dynamically. The level of private donations in one period may affect the level of government grants in the following period. While this effect was partly tested in Tables 3.3 and 3.4 when I used lagged values of the regressor, an alternative way to test for that causality is through vector autoregressions. Specifically, I use the method developed in Holtz-Eakin et. al. (1988) to perform vector autoregressions on panel data. This methodology is also used

[93] An alternative instrument might be to look at the county level attainment status of National Ambient Air

on data from charities in Connolly (1997) and Segal and Weisbrod (1998), though neither paper looks for crowding out between government grants and private donations. Using this method, I test for the presence of Granger causality between these two values, in both directions. The procedure involves taking first differences to eliminate a charity fixed effect, and using lagged values as instruments.

The results of these vector autoregressions are presented in Table 3.7. The negative coefficients in both directions for environmental charities suggest crowding out in both directions, and for social service charities the positive coefficients suggest crowding in. However, all values are small, and the p-value of the test for Granger causality indicates that Granger non-causality cannot be rejected. The lack of significant results may be due to the fact that none of the controls or instruments used earlier is used here. Instead, this is just a vector autoregression of private donations and government grants.

**Table 3.7**

| **Vector Autoregressions** | | | |
|---|---|---|---|
| | | Environmental Charities | Social Service Charities |
| Government grants Granger cause Private Donations | Coefficient | -.00673 | .0344 |
| | p-value | .9945 | .9950 |
| Private Donations Granger cause Government grants | Coefficient | -.0114 | .0144 |
| | p-value | .9772 | .9932 |

*Notes*: Data are from 1998-2003 and only include those organizations that are in the panel for all six years and whose reported categorical revenues sum up to reported total revenues, and likewise for expenses. Coefficient value is the impact of previous year's government grants on current year's private donations, or vice versa.

## 3.5. Conclusion

The effect of crowding out of private donations by government contributions, proposed in Warr (1982) and Roberts (1984), and extended to include a warm glow effect

Quality Standards.

in Andreoni (1989, 1990), has had numerous empirical investigations. Many studies, including Kingma (1989) and Payne (1998) find significant evidence of partial crowding out. Other papers, including Khanna and Sandler (2000) and Payne (2001), find some evidence of crowding in of private donations. Though their results differ, most of these papers have several things in common: they use a relatively small sample of charities, they look at social service charities, and they test for crowding out in only one direction.

Here I extend that literature by looking at a large data set that includes most charities that file Form 990 with the IRS, which includes all non-religious charities with at least $25,000 in gross receipts. Because I attempt to instrument for private donations by announcements regarding endangered species and toxic emissions, I look separately at environmental and animal related charities, in addition to social service charities. The main contribution is the theoretical and empirical examination of crowding out in the "opposite direction": private donations crowding out government grants. Theoretically, I show that the crowding out effect depends on whether the government or individuals make their contributions first.

Empirically, I find more evidence for crowding *in* than for crowding *out*. Not only am I unable to find crowding out of government grants by private donations, I am unable to find the more traditional direction of crowding out of private donations by government grants. Among the social service charities, evidence supports crowding in of private donations by government grants. Rose-Ackerman (1986) describes conditions under which government grants can crowd in private donation. For instance, matching grants are likely to spur an increase in donations. Grants may also come with mandated regulatory changes that make the charity more appealing to donors. If a charity exhibits economies of scale, then increased government revenue reduces the marginal cost of providing the service, making private donations more effective. Finally, grants may provide information, either explicitly through mandated reporting, or implicitly through the signal provided by the grant's acceptance. Similarly, in a model of revenues of research universities, Payne (2001) shows that if government and private funds are complementary or if government funding acts as a signal of institutional quality, then crowding in effects may dominate crowding out effect. It is possible that this is the case for the social service charities studied here, while for the environmental charities the two effects perfectly offset each other.[94] A signaling model of contributions to charities is presented in Andreoni (1998). There, "seed money" from large donors increases others' donations by acting as a signal of the charity's quality. Evidence of this effect was found in a field experiment in List and Lucking-Reiley (2002). The crowding in found here suggests that government grants act as a signal to donors in the same way that seed money does.

One reason for unexpected results may be that by looking only at data from charities, I am unable to capture any other types of crowding out behavior that may be unrelated to the charities. For example, in response to an increase in government grants to environmental charities, individuals may not reduce their contributions to charities, but instead reduce their level of volunteering or recycling.[95] Similarly, governments may respond to an increase in private donations by decreasing funding to the EPA or other environmental activities besides the particular charity affected. This would bias downward my estimates of crowding out.

In addition, the only data I have on government contributions to these public goods are through grants made to nonprofit groups. Governments also provide public goods in other ways. According to White House audits, the total amount of federal grants to environmental charities in 2004 was $143 million, whereas the 2005 EPA budget totaled $7.8 billion. Much of the EPA's spending went to grants paid to states and tribal governments, which may in turn have used that federal money to pay grants to environmental charities. But it is clear that at least some and perhaps a large fraction of the money that government uses to provide environmental and social service public goods are provided in other ways besides grants to charities. How this effect may bias the results is unclear. If grants to charities are a constant fraction of government spending on public goods, then no bias exists, since the increase that I see in the data in

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[94] Though they test for crowding out between program service revenue and all contributions, public and private, Segal and Weisbrod (1998) also find different results for different types of charities. Crowding out is found for housing, shelter, and arts charities, while crowding in is found for universities, technological institutes, and human services charities.

government grants to charities corresponds to an increase in actual government provision of public goods. However, if the government substitutes nonprofit grants for other spending on public goods (so that when I see an increase in grants in the data, the actual government provision of public goods may have stayed constant or decreased), then the results may be biased.

Though the evidence does not support the predictions of the model, this paper makes several valuable contributions. First, the theoretical suggestion that private donations crowd out government contributions may manifest itself in other types of charities besides the ones studied here. Second, I have shown that environmental charities are very different from social service charities in their sources of revenue. The previous literature on crowding out has focused on social service charities, so it is important not to apply their results to other types of charities, including environmental, arts, or education charities. Third, the extensive data set used is an improvement over previous studies that have looked at smaller sample sizes. In fact, the results I get from social service charities contradict many of those studies, since I find evidence of crowding in, as do Khanna and Sandler (2000). The issue of crowding out of charitable contributions, important for questions about optimal funding of public goods, is as yet unresolved.

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[95] Simmons and Emanuele (2004) find that government grants crowd out donations of both money and time.

## Appendix A1: Proof of Propositions 1 and 2

*Proof of Proposition 1*

Consider first the policy of emissions taxes without grandfathering. Following Cooper et. al. (1999), let $(v, u, A, B)$ • $V^A(v, u, A, B) - V^N(v, u, A, B)$, or the additional value from adjusting compared to not adjusting. This expression equals

$$\begin{aligned}&Af(v)\lambda - F - \tau Bg(v) + \beta(1-\delta)EV(1,u,A',B') \\ &-[Af(v) - \tau Bg(v) + \beta(1-\delta)EV(v+1,u,A',B')] \\ &= Af(v)(\lambda - 1) - F + \beta(1-\delta)E(V(1,u,A',B') - V(v+1,u,A',B'))\end{aligned}.$$

The first term is increasing in $v$ since $f(v)$ is decreasing in $v$ and $- 1$ is negative. The final term in also increasing in $v$ since $V(v, A, B)$ is decreasing in $v$. Since $(v,u, A, B)$ is increasing in $v$ for all $A$ and $B$, then any function $H(v, A, B)$ that integrates over the unobserved components of $A$ or $B$ is also increasing in $v$.

*Proof of Proposition 2*

Define $(v, u{=}0, A, B)$ • $V^A(v, u{=}0, A, B) - V^N(v, u{=}0, A, B)$ and $(v, u{=}1, A, B)$ • $V^A(v, u{=}1, A, B) - V^N(v, u{=}1, A, B)$. From the proof above, it is known that

$$\begin{aligned}\Delta(v,u=0,A,B) &= Af(v)(\lambda - 1) - F + \beta(1-\delta)E(V(1,u=1,A',B') - V(v+1,u=0,A',B')) \\ \Delta(v,u=1,A,B) &= Af(v)(\lambda - 1) - F + \beta(1-\delta)E(V(1,u=1,A',B') - V(v+1,u=1,A',B'))\end{aligned}.$$

Therefore,

$$\Delta(v,u=0,A,B) - \Delta(v,u=1,A,B) = \beta(1-\delta)E(V(v+1,u=1,A',B') - V(v+1,u=0,A',B')).$$

This expression must be less than zero, since $V(v, u{=}0, A, B)$ must be greater than $V(v, u{=}1, A, B)$ because grandfathering is valuable to plants. From similar arguments above, this implies that $H(v, u = 0, A, B) < H(v, u = 1, A, B)$.

## Appendix A2: Finding the Substitution Elasticities $b_{ij}$

The $b_{ij}$ elasticities are evaluated from the production function in the dirty sector in a manner analogous to Allen (1938, p. 505-508). We are solving for the derivatives of input demands with respect to changes in either input prices or , the policy parameter. These input demand equations come from the firm's cost minimization problem, where the total quantity to be produced is exogenous. First consider a small change in the price of capital, $dr$. If we differentiate the production function with respect to $r$ we get

$$Y_K \frac{dK_Y}{dr} + Y_L \frac{dL_Y}{dr} + Y_Z \frac{dZ}{dr} = \frac{dY}{dr} = 0,$$

where the last equation comes from the fact that total output demanded is exogenous and not a function of the rental rate.

The first order condition of the minimization problem with respect to the choice of $K_Y$ is $\frac{p_Y}{1-\delta Y_Z} Y_K = r$. Differentiate this equation with respect to $r$, multiply through by $\frac{1-\delta Y_Z}{p_Y}$, and collect terms to get

$$\frac{Y_K}{p_Y}\frac{dp_Y}{dr} + [Y_{KK} + Y_K Y_{ZK}\xi]\frac{dK_Y}{dr} + [Y_{KL} + Y_K Y_{ZL}\xi]\frac{dL_Y}{dr} + [Y_{KZ} + Y_K Y_{ZK}\xi]\frac{dZ}{dr} = \frac{1-\delta Y_Z}{p_Y},$$

where $\xi \equiv \frac{\delta}{1-\delta Y_Z}$. Similarly, differentiate the next first order condition, $\frac{p_Y}{1-\delta Y_Z} Y_L = w$, with respect to $r$ and rearrange to get

$$\frac{Y_L}{p_Y}\frac{dp_Y}{dr} + [Y_{LK} + Y_L Y_{ZK}\xi]\frac{dK_Y}{dr} + [Y_{LL} + Y_L Y_{ZL}\xi]\frac{dL_Y}{dr} + [Y_{LZ} + Y_L Y_{ZK}\xi]\frac{dZ}{dr} = 0.$$

Note that the right hand side of this equation is zero, since a change in $r$ has no effect on $w$, which is exogenous to this input demand system. Finally, the policy constraint binds, so $Z = \ Y$. Since $Y$ and   are both exogenous variables in the input demand system, a change in $r$ has no effect on their values. Hence, differentiating this equation with respect to $r$ yields $\frac{dZ}{dr} = 0$.

Writing these four equations in matrix form allows use of Cramer's rule to evaluate the derivatives. This equation is

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K & Y_{KK} + Y_K Y_{ZK}\xi & Y_{Kl} + Y_K Y_{ZL}\xi & Y_{KZ} + Y_K Y_{ZZ}\xi \\ Y_L & Y_{LK} + Y_L Y_{ZK}\xi & Y_{LL} + Y_L Y_{ZL}\xi & Y_{LZ} + Y_L Y_{ZZ}\xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{dr} \\ dK_Y/dr \\ dL_Y/dr \\ dZ/dr \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{1-\delta Y_Z}{p_Y} \\ 0 \\ 0 \end{bmatrix}$$

Follow the notation of Allen (1938) and use $F$ to denote the determinant of the bordered Hessian of the production function, and use $F_{ij}$ to denote the cofactor of element $i,j$ of that matrix. The determinant of the matrix of coefficients in the above equation simplifies to $F_{ZZ}$ (the terms with   all cancel each other out). With an odd number of inputs, the assumption of constant returns to scale (linear homogeneity) implies that $F < 0$ and $F_{ZZ} > 0$. Using Cramer's rule, we solve for the derivatives of interest:

$$\frac{dK_Y}{dr} = \frac{-(Y_L)^2(1-\delta Y_Z)}{p_Y F_{ZZ}} < 0 \ , \quad \frac{dL_Y}{dr} = \frac{Y_L Y_K (1-\delta Y_Z)}{p_Y F_{ZZ}} > 0 \, .$$

These sign indicate that $b_{KK} < 0$ and $b_{LK} > 0$, as we now show. The term $1 - \ Y_Z$ is strictly positive for the following reason. The policy parameter   $= Z/Y$ is the inverse of *average* output per unit of $Z$. It is multiplied by $Y_Z$, the *marginal* output per unit of $Z$. Since production is constant returns to scale, the average output must exceed the marginal output, and hence $\ Y_Z < 1$. Furthermore, both first derivatives of $Y$ are positive, and $F_{ZZ} < 0$ as mentioned before. Thus $b_{KK} < 0$ and $b_{LK} > 0$.

We take the production function, the first order conditions for the cost minimization problem, and the binding constraint, and then we differentiate all, this time with respect to $w$. Writing these four equations in matrix form yields a similar system of equations:

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K & Y_{KK}+Y_K Y_{ZK}\xi & Y_{Kl}+Y_K Y_{ZL}\xi & Y_{KZ}+Y_K Y_{ZZ}\xi \\ Y_L & Y_{LK}+Y_L Y_{ZK}\xi & Y_{LL}+Y_L Y_{ZL}\xi & Y_{LZ}+Y_L Y_{ZZ}\xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{dw} \\ dK_Y/dw \\ dL_Y/dw \\ dZ/dw \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \frac{1-\delta Y_Z}{p_Y} \\ 0 \end{bmatrix}.$$

The matrix of coefficients is the same as for $dr$ above; the only difference is in which element of the vector of constants is nonzero. Here it is the element corresponding to the differentiation of the first order condition for labor input, since $w$ is changing. Solving this system yields

$$\frac{dK_Y}{dw} = \frac{Y_K Y_L(1-\delta Y_Z)}{p_Y F_{ZZ}} > 0 \ , \quad \frac{dL_Y}{dw} = \frac{-(Y_K)^2(1-\delta Y_Z)}{p_Y F_{ZZ}} < 0 \, .$$

These solutions can be used to evaluate the input demand elasticities.

$$b_r = b_{KK} - b_{LK} = \frac{r}{K_Y}\frac{dK_Y}{dr} - \frac{r}{L_Y}\frac{dL_Y}{dr} = \frac{r(1-\delta Y_Z)Y_L}{p_Y F_{ZZ}}\left(-\frac{Y_L}{K_Y} - \frac{Y_K}{L_Y}\right) < 0$$

$$b_w = b_{KL} - b_{LL} = \frac{w}{K_Y}\frac{dK_Y}{dw} - \frac{w}{L_Y}\frac{dL_Y}{dw} = \frac{w(1-\delta Y_Z)Y_K}{p_Y F_{ZZ}}\left(\frac{Y_L}{K_Y} + \frac{Y_K}{L_Y}\right) > 0 \, .$$

We can substitute in the first order conditions $p_Y Y_K = r(1 - \ Y_Z)$ and $p_Y Y_L = w(1 - \ Y_Z)$ to simplify these expressions.

$$b_r = -\frac{Y_K Y_L}{F_{ZZ}}\left(\frac{Y_L}{K_Y} + \frac{Y_K}{L_Y}\right) \ , \quad b_w = \frac{Y_K Y_L}{F_{ZZ}}\left(\frac{Y_L}{K_Y} + \frac{Y_K}{L_Y}\right) .$$

This substitution demonstrates that $b_r = -b_w$.

Lastly, we want to find the derivatives of factor demands with respect to a change in the policy parameter . Again, differentiate the production function and the first order conditions, here with respect to . The policy constraint $(Z = \ Y)$ differentiated with respect to yields $dZ/d\delta = Y$. The matrix form of this system of equations is

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K & Y_{KK}+Y_K Y_{ZK}\xi & Y_{Kl}+Y_K Y_{ZL}\xi & Y_{KZ}+Y_K Y_{ZZ}\xi \\ Y_L & Y_{LK}+Y_L Y_{ZK}\xi & Y_{LL}+Y_L Y_{ZL}\xi & Y_{LZ}+Y_L Y_{ZZ}\xi \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{d\delta} \\ dK_Y/d\delta \\ dL_Y/d\delta \\ dZ/d\delta \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{Y_Z Y_K}{1-\delta Y_Z} \\ -\frac{Y_Z Y_L}{1-\delta Y_Z} \\ Y \end{bmatrix}.$$

Again the matrix of coefficients is the same, with determinant $F_{ZZ}$. Solving for the derivatives of interest yields:

$$\frac{dK_Y}{d\delta} = Y\frac{F_{KZ}}{F_{ZZ}} \quad , \quad \frac{dL_Y}{d\delta} = Y\frac{F_{LZ}}{F_{ZZ}},$$

where again $F_{ij}$ denotes the cofactor of element $i,j$ in the bordered Hessian of the production function. These cofactors are not immediately interpretable, but they are an integral part of the definition of the Allen elasticities. They are defined as:

$e_{ij} \equiv \frac{p_Y Y}{i_Y j_Y} \cdot \frac{F_{ij}}{F}$, where $i_Y$ is the quantity of input $i$ used. With these definitions we can calculate the remaining input demand elasticities:

$$b_\delta = b_{KZ} - b_{LZ} = \frac{\delta}{K_Y}(Y\frac{F_{KZ}}{F_{ZZ}}) - \frac{\delta}{L_Y}(Y\frac{F_{LZ}}{F_{ZZ}}) = \frac{\delta Z}{p_Y}\frac{F}{F_{ZZ}}(e_{KZ} - e_{LZ}),$$

where $e_{ij}$ is the Allen elasticity of substitution between inputs $i$ and $j$. Since $F/F_{ZZ} < 0$, the sign of $b$ is opposite the sign of $e_{KZ} - e_{LZ}$; if capital is a better substitute for pollution than is labor, then $b$ is negative.

**Appendix A3: Finding the Substitution Elasticities $c_{ij}$**

We calculate these elasticities using a method similar to the one in Appendix A2. First, consider the effect of small changes in the capital rental rate. If we differentiate the production function with respect to $r$ we get, as before:

$$Y_K\frac{dK_Y}{dr} + Y_L\frac{dL_Y}{dr} + Y_Z\frac{dZ}{dr} = \frac{dY}{dr} = 0$$

The first order condition from the maximization problem with respect to capital is $r = p_Y(Y_K + \quad Y_Z)$. Differentiate this with respect to $r$, divide through by $p_Y$, and rearrange terms to get:

$$\frac{Y_K + \zeta Y_Z}{p_Y}\frac{dp_Y}{dr} + [Y_{KK} + \zeta Y_{ZK}]\frac{dK_Y}{dr} + [Y_{KL} + \zeta Y_{ZL}]\frac{dL_Y}{dr} + [Y_{KZ} + \zeta Y_{ZK}]\frac{dZ}{dr} = \frac{1}{p_Y}.$$

The first order condition for labor is $w = p_Y Y_L$. Differentiating this equation by $r$ and similarly rearranging yields

$$\frac{Y_L}{p_Y}\frac{dp_Y}{dr} + Y_{LK}\frac{dK_Y}{dr} + Y_{LL}\frac{dL_Y}{dr} + Y_{LZ}\frac{dZ}{dr} = 0.$$

Finally, differentiate the policy constraint $Z = \quad K_Y$ by $r$ to obtain

$$\frac{dZ}{dr} = \zeta\frac{dK_Y}{dr}.$$

Combining these four equations into matrix form allows us to solve for any of the derivatives. This matrix equation is

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K + \zeta Y_Z & Y_{KK} + \zeta Y_{ZK} & Y_{Kl} + \zeta Y_{ZL} & Y_{KZ} + \zeta Y_{ZZ} \\ Y_L & Y_{LK} & Y_{LL} & Y_{LZ} \\ 0 & \zeta & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{dr} \\ dK_Y/dr \\ dL_Y/dr \\ dZ/dr \end{bmatrix} = \begin{bmatrix} 0 \\ 1/p_Y \\ 0 \\ 0 \end{bmatrix}.$$

We solve for these derivatives using Cramer's Rule, where the denominator is the determinant of the matrix of coefficients. Call this denominator $D$. Solving along the bottom row, and using known properties of determinants, we get:

$$D = \zeta(F_{KZ} + \zeta(-F_{KK})) - (F_{ZZ} + \zeta(-F_{KZ})) = -\zeta^2 F_{KK} - F_{ZZ} + 2\zeta F_{KZ},$$

where the $F_{ij}$ notation is from Allen (1938), just as in the previous section. We can solve for this denominator in terms of the Allen elasticities using their definitions:

$$D = -\zeta^2\frac{Fe_{KK}K_Y{}^2}{p_Y Y} - \frac{Fe_{ZZ}Z^2}{p_Y Y} + 2\zeta\frac{Fe_{KZ}K_Y Z}{p_Y Y}.$$

And, since $= Z/K_Y$,

$$D = \frac{FZ^2}{p_Y Y}(-e_{KK} - e_{ZZ} + 2e_{KZ}).$$

We can sign the denominator with information about these three Allen elasticities. The ratio in the front of this expression is negative, since $F < 0$ and all of the other constants are positive. The own-price elasticities $e_{KK}$ and $e_{ZZ}$ must be negative. Hence, $D$ is negative if and only if $e_{KZ}$ is not too negative:

$$\text{Condition 2:} \quad e_{KZ} > \frac{e_{KK} + e_{ZZ}}{2}.$$

Since the right hand side of this inequality is strictly negative, a sufficient condition for $D$ to be negative is capital and pollution are substitutes in production ($e_{KZ} > 0$). However, $D$ is still negative if $K$ and $Z$ are not too complementary.

We now use Cramer's Rule to solve for the derivatives.

$$\frac{dK_Y}{dr} = \frac{1}{D}\frac{Y_L^{\,2}}{p_Y}, \qquad \frac{dL_Y}{dr} = -\frac{1}{D}\frac{Y_L(Y_K + \zeta Y_Z)}{p_Y}.$$

When $D < 0$, then $dK_Y/dr < 0$ and $dL_Y/dr > 0$. We can also use Cramer's rule to solve for $dZ/dr$, but differentiation of the policy constraint provides it as a function of $dK_Y/dr$.

Now, we solve for the elasticities $c_{KK}$ and $c_{LK}$, and the difference (which is defined as $c_r$ in the text):

$$c_r \equiv c_{KK} - c_{LK} \equiv \frac{r}{K_Y}\frac{dK_Y}{dr} - \frac{r}{L_Y}\frac{dL_Y}{dr} = \frac{r}{K_Y}\frac{Y_L^{\,2}}{Dp_Y} + \frac{r}{L_Y}\frac{Y_L(Y_K + \zeta Y_Z)}{Dp_Y} = \frac{rY_L}{Dp_Y}\left(\frac{Y_L}{K_Y} + \frac{Y_K + \zeta Y_Z}{L_Y}\right)$$

The sign of $c_r$ is thus equal to the sign of $D$.

The same method is used to solve for the derivatives with respect to $w$ and .
Differentiating the four equations with respect to $w$ yields:

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K + \zeta Y_Z & Y_{KK} + \zeta Y_{ZK} & Y_{Kl} + \zeta Y_{ZL} & Y_{KZ} + \zeta Y_{ZZ} \\ Y_L & Y_{LK} & Y_{LL} & Y_{LZ} \\ 0 & \zeta & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{dw} \\ dK_Y/dw \\ dL_Y/dw \\ dZ/dw \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1/p_Y \\ 0 \end{bmatrix}.$$

The denominator again is $D$. Solving for the derivatives gives:

$$\frac{dK_Y}{dw} = -\frac{1}{D}\frac{Y_L(Y_K + \zeta Y_Z)}{p_Y} \quad , \qquad \frac{dL_Y}{dw} = \frac{1}{D}\frac{(Y_K + \zeta Y_Z)^2}{p_Y}.$$

So if $D < 0$, then $dK_Y/dw > 0$ and $dL_Y/dw < 0$. This gives us an expression for $c_w$:

$$c_w \equiv c_{LK} - c_{LL} = \frac{w}{K_Y}\frac{-Y_L(Y_K + \zeta Y_Z)}{Dp_Y} - \frac{w}{L_Y}\frac{(Y_K + \zeta Y_Z)^2}{Dp_Y} = -\frac{w(Y_K + \zeta Y_Z)}{Dp_Y}\left(\frac{Y_L}{K_Y} + \frac{(Y_K + \zeta Y_Z)}{L_Y}\right)$$

The sign of $c_w$ is the opposite of the sign of $D$.

Finally, we differentiate the four equations with respect to to generate:

$$\begin{bmatrix} 0 & Y_K & Y_L & Y_Z \\ Y_K + \zeta Y_Z & Y_{KK} + \zeta Y_{ZK} & Y_{Kl} + \zeta Y_{ZL} & Y_{KZ} + \zeta Y_{ZZ} \\ Y_L & Y_{LK} & Y_{LL} & Y_{LZ} \\ 0 & \zeta & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{p_Y}\frac{dp_Y}{d\zeta} \\ dK_Y/d\zeta \\ dL_Y/d\zeta \\ dZ/d\zeta \end{bmatrix} = \begin{bmatrix} 0 \\ -Y_Z \\ 0 \\ -K_Y \end{bmatrix}.$$

The difference on the right hand side comes from the fact that, when differentiating with respect to , the term can no longer be treated as a constant. For example, the policy constraint $Z = \ K_Y$ when differentiated yields $\frac{dZ}{d\zeta} = K_Y + \zeta\frac{dK_Y}{d\zeta}$, the bottom row of the matrix equation.

The denominator is the same as in earlier cases. Solving for the derivatives gives:

$$\frac{dK_Y}{d\zeta} = \frac{1}{D}(-Y_L{}^2 Y_Z - K_Y(F_{KZ} - \zeta F_{KK})),$$

$$\frac{dL_Y}{d\zeta} = \frac{1}{D}(Y_L Y_Z (Y_K + \zeta Y_Z) - K_Y (F_{LZ} - \zeta F_{KL})).$$

The first derivative above consists of two offsetting terms whenever capital and pollution are substitutes, since $D < 0$, $F_{KZ} < 0$, and $F_{KK} > 0$. Therefore, when policy is tightened and   falls, then demand for capital may fall or rise. The sign of the derivative of labor demand with respect to   is also ambiguous. It depends on both $D$ and the relative magnitude of $F_{KZ}$ and $F_{LZ}$, or $e_{KZ}$ and $e_{LZ}$.

Solving for the elasticity $c_\zeta \equiv c_{ZK} - c_{ZL} \equiv \frac{\zeta}{K_Y}\frac{dK_Y}{d\zeta} - \frac{\zeta}{L_Y}\frac{dL_Y}{d\zeta}$, we get:

$$c_\zeta = \frac{\zeta}{K_Y}\frac{-Y_L{}^2 Y_Z - K_Y(F_{KZ} - \zeta F_{KK})}{D} - \frac{\zeta}{L_Y}\frac{Y_L Y_Z (Y_K + \zeta Y_Z) - K_Y(F_{LZ} - \zeta F_{KL})}{D}$$

$$= \frac{\zeta}{D}(-Y_L Y_Z (\frac{Y_L}{K_Y} + \frac{Y_K + \zeta Y_Z}{L_Y}) + \frac{FK_Y Z}{p_Y Y}(-e_{KZ} + e_{KK} + e_{LZ} - e_{KL}))$$

The sign of this term depends on the relationship between the three Allen cross-price elasticities, but it is complicated. Let $M$ equal the first term in the parentheses multiplied by  . Factoring  $/D$ into the second term, the terms in front all cancel out and it becomes $\frac{e_{LZ} - e_{KZ} + e_{KK} - e_{KL}}{-e_{KK} - e_{ZZ} + 2e_{KZ}}$. The expression for $c$  can then be written as it is in the text in section 5.1.

Finally, note that the equations relating the $c_{ij}$ elasticities from the text, $c_{KK} - c_{ZK} = 0$, $c_{KL} - c_{ZL} = 0$, and $c_{KZ} - c_{ZZ} = -1$, can be verified using the derivations of the appropriate elasticities.

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